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Airborne RF Measurement System (ARMS) and Analysis of Representative Flight RF Environment

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July 2007

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List of Acronyms

ARMS	Airborne Radio Frequency Measurement System
CNS	Communication, Navigation, and Surveillance
COM	Communication
DTV	Digital Television
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
GPS	Global Positioning System
GS	Glideslope
IAP	International Approach Procedure
ILS	Inertial Landing System
LOC	Localizer
NAS	National Airspace System
NAV	Navigation
NTSC	National Television System Committee
RF	Radio Frequency
SA	Spectrum analyzer
VOR	Very High Frequency Omni-Range
VSWR	Voltage Standing Wave Ratio

Abstract

Environmental radio frequency (RF) data over a broad band of frequencies (30 MHz to 1000 MHz) were obtained to evaluate the electromagnetic environment in airspace around several airports. An RF signal measurement system was designed utilizing a spectrum analyzer connected to the NASA Lancair Columbia 300 aircraft's VHF/UHF navigation antenna. This paper presents an overview of the RF measurement system and provides analysis of sample RF signal measurement data. This aircraft installation package and measurement system can be quickly returned to service if needed by future projects requiring measurement of an RF signal environment or exploration of suspected interference situations.

1 Introduction

The National Airspace System (NAS) is becoming increasingly dependent upon radio-based communication, navigation and surveillance (CNS) services between aircraft, ground and satellite infrastructures. Radio frequency (RF) electromagnetic compatibility (EMC) between radio-based CNS services and the electromagnetic environment is important for management of the current and future RF environment for aeronautics and space based operations.

As part of NASA's mission to develop technologies for safer aircraft, the agency is conducting research in electromagnetic threats and hazards to safe flight. Development of the Airborne RF Measurement System (ARMS) is part of this effort. The purpose of the ARMS is to provide a resource for environmental electromagnetic measurements. It can be used to investigate high-intensity radiated fields (HIRF) and RF spectrum encroachments.

Recently, the ARMS was used during a flight experiment to evaluate the electromagnetic environment in the airspace during approaches to a local airfield. The ARMS installation package provided the ability to monitor, collect, and record RF signal measurements and Global Positioning System (GPS) data utilizing a laptop computer and a spectrum analyzer connected to an aircraft's navigation (NAV) antenna.

The NASA Langley Research Center's (LaRC) Lancair Columbia 300 aircraft was selected because of its operational capabilities, low fuel consumption, availability, and acceptable cargo capacity. Operationally, the Lancair aircraft provided instrumentation for acquiring GPS data and performing precision approaches and landings. Other operational advantages included two identical navigation and communication (NAVCOM) radio units, easily accessible avionics equipment, and speed and altitude performance suitable for the required experiment measurements. A minimal crew was required, consisting of one pilot to fly the aircraft and one researcher to operate the measurement system.

During design and development, the aircraft was subjected to numerous performance and safety analyses. Critical design reviews were conducted and attended by research engineers, systems engineers, and flight test operations personnel that included pilots, engineers, and ground crews. The LaRC Airworthiness and Safety Review Board reviewed and approved the safety analyses.

This paper presents an overview of the ARMS, its installation on the Lancair Columbia 300 aircraft, and provides a sample of RF signal measurement data obtained during a recent NASA flight experiment. Development of the measurement system is described, followed by a description of system operation. Sample data is presented from the NASA flight experiment to evaluate the airspace's electromagnetic environment during approaches to a local airfield. Calibration of measured data presents a challenging problem for this system when performing broad spectral sweeps using a standard aircraft antenna tuned for a particular RF band. The application of calibrations for

particular scenarios is discussed in a later section. The final section presents a few observations made during development and recommendations for future applications.

2 System Description

Requirements and development of the ARMS' electrical and mechanical systems are presented, as well as a description of its software instrument control and data collection capabilities.

Figure 2-1 is a block diagram illustrating the ARMS installation package for the NASA Lancair aircraft and the aircraft equipment used. The ARMS installation package is comprised of four elements: research electrical power and communication interfaces, mechanical system, instrumentation, and software. ARMS utilizes aircraft equipment resources to provide electrical power and communication interfaces. It also uses aircraft antennas and receivers for acquiring RF signals, GPS data, and for performing precision approaches and landings.

Within the ARMS installation package the research electrical system includes communication interfaces, power converters, and input power for instrumentation derived from the aircraft's installed baseline research electrical power system. The mechanical system includes instrumentation pallets, fasteners, and restraints to safely mount ARMS instrumentation. The software provides instrument control and data collection. Additionally, the ARMS includes a spectrum analyzer (SA) for RF signal measurement, a laptop computer for data collection, and communication interfaces.

The Lancair aircraft's baseline research electrical and mechanical systems were modified to accommodate the ARMS' requirements. Electrical power converters were added to provide for the required instrument input power. Emergency cutoff switches were installed as part of the baseline research system to meet aircraft safety requirements. The installation of research equipment required that instrument pallets and restraints be designed and incorporated into the aircraft. The baseline research electrical system, the mechanical system, and modifications made to accommodate ARMS are discussed in later sections.

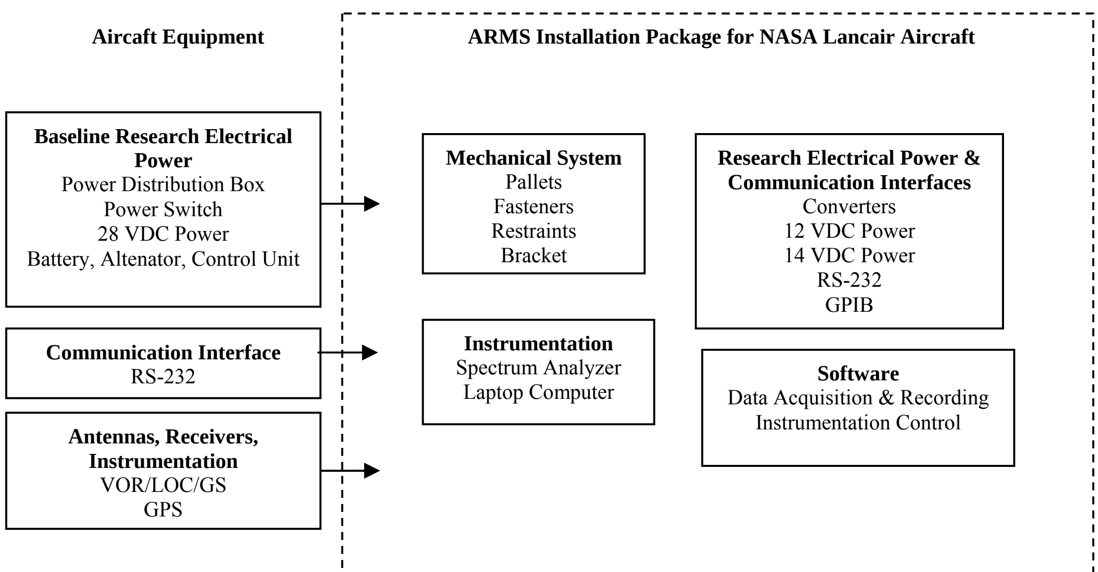


Figure 2-1: ARMS installation package on NASA Lancair aircraft.

Figure 2-2 illustrates the ARMS measurement instrumentation, communication interfaces (blue), and the aircraft's GPS and NAV systems. The laptop computer communicates with the spectrum analyzer via an IEEE General Purpose Interface Bus (GPIB) to collect RF measurement data and to control the spectrum analyzer parameters. GPS data is collected by the laptop computer using an IEEE RS-232 interface connected to the aircraft's GPS receiver which is attached to the aircraft's GPS antenna. RF signals are received using the aircraft's NAV antenna for Very High Frequency Omni-Range (VOR), Localizer (LOC), and Glideslope (GS) bands.

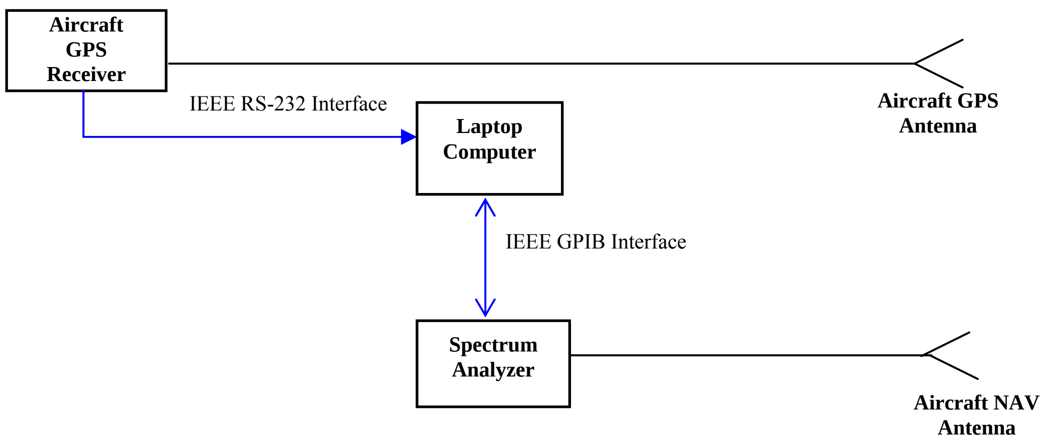


Figure 2-2: ARMS measurement instrumentation and communication interfaces.

A view of the Lancair aircraft is presented in Figure 2-3, as well as a close up of the tail section identifying the location of the NAV antenna, a Comant CI 159C dual-band V-Dipole, manufactured by Comant Industries, and used for VOR, LOC, and GS bands. NAV antenna characteristics and polar plots are discussed in Appendix A. The GPS antenna (not visible in the picture) is located inside the aft fuselage, which is of composite construction.

Figure 2-3: Lancair Columbia 300 aircraft and NAV antenna located on tail.

Figure 2-4: Installation of ARMS test equipment on the Lancair Columbia 300 aircraft.

2.1 Electrical System

This section discusses the Lancair aircraft baseline research electrical system configuration and the modifications to accommodate the ARMS installation package on the NASA Lancair aircraft. The Lancair aircraft's research system is based on a baseline research system presented in a paper entitled "NASA Langley Research Center's General Aviation Baseline Research System" (GABRS) [ref. 1]. The document describes design for development of a common baseline research system to support research activities in NASA Langley's General Aviation (GA) aircraft. The ARMS installation package added capabilities beyond those included in the baseline research system.

2.1.1 Aircraft Baseline Research Electrical System

The electrical power for the research system was designed to provide an independent source of electrical power for the research systems while maintaining isolation from the basic aircraft's electrical system. Safety requirements included that the pilot be able to turn off experimental equipment during critical phases of flight, that any crew member or occupant be able to shut down the system if the need arises, that research system power be isolated from basic ship power, and that no ties to the flight controls or autopilot from the research system exist.

Figure 2-5 illustrates the baseline research electrical system that consists of the following components: A Northcoast Technologies alternator, a Concord sealed lead-acid battery, an Electrodelta alternator control unit, a research power distribution box, and research power control panels. Figure 2-6 illustrates the research power control panels located in the Lancair aircraft. Additional components include research pallet electrical interfaces and ground power connection and wiring.

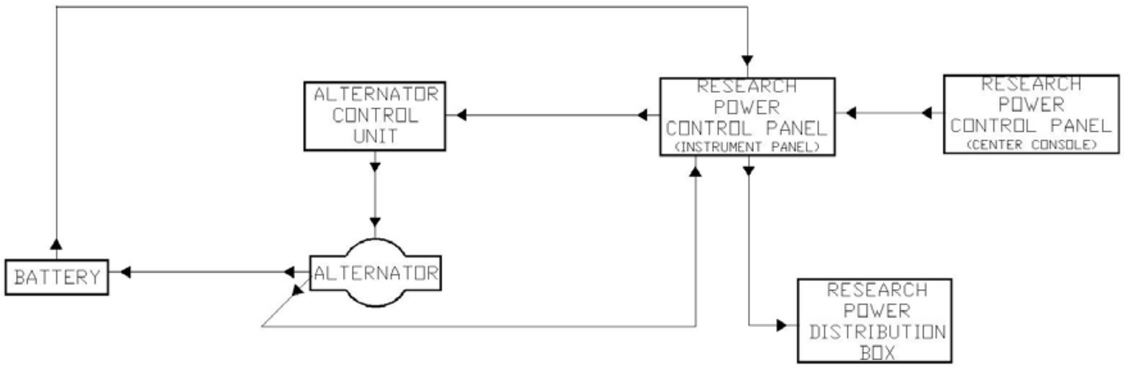


Figure 2-5: Lancair aircraft baseline research electrical system.

Two Research Power Control Panels were installed in the Lancair aircraft (Figure 2.6) in order to meet the flight safety requirements for controlling the research system power. A Research Power Control Panel was installed in the right instrument panel and a secondary Research Power Control Panel was also installed in the center console. The Instrument Panel mounted Research Power Control Panel provides the front seat occupants (pilot and copilot) the ability to control the operation and monitor the status of the research power system. The Center Console mounted Research Power Control Panel provides a secondary centralized control location that is easily accessible by the entire crew. The power switches are wired in series and both must be "ON" for the system to operate. The researcher or pilot can operate either switch to shut down the entire research power system in the event of an aircraft system failure, an in-flight emergency or questionable system integrity.

The Instrument Panel mounted Research Power Control Panel consists of two locking toggle switches, annunciators, circuit breakers, and a digital meter. Two locking toggle switches provide control of the research power system: one energizes the research system battery and alternator control unit; the other switch controls the research power. The annunciators and meter provide indications that allow the monitoring of system status (power on), voltage, current, under-voltage, and alternator failure. The circuit breakers provide individual circuit protection and isolation for the meter, alternator control unit, alternator field voltage, annunciators, and research power output.

The Center Console mounted Research Power Control Panel's primary function is to provide a second research power control toggle switch. Additionally, it contains switches and indicators for control and status indication of a video recording system and a data acquisition system which were not required for the ARMS during this survey, but may be useful for other experiments.

A research power distribution box, located on the aft research pallet (Figure 2-7), is used to provide a centralized location for the distribution of power and circuit protection for the research system equipment. The research power system provides 50 A at 28 VDC (1.4 KW) to the distribution box. The distribution box contains two internal voltage converters providing 9 VDC (not used by ARMS) and 12 VDC outputs. All outputs from the distribution box are circuit breaker protected, providing an additional means of individual circuit isolation and control.

Figure 2-7 shows the RS-232 Monitor Port and Source Select Switch located on the front of the aft research pallet in the Lancair aircraft. These provide access via the RS-232 interface to the aircraft avionics suite #1 and #2 COM/NAV transceivers, transponder, altitude encoder, a multifunction display, and GPS receiver. Using the Source Select Switch, any or all of the RS-232 data is available and can be interfaced with a compatible research system as required. The ARMS used the RS-232 Monitor Port to interface with the GPS receiver. The RS-232 interface is configured to allow transmitted data from the aircraft's avionics to be received at the aft research pallet, but data from the pallet can not be transmitted to the avionics, thereby reducing the potential for corruption or interference with the aircraft systems.

Figure 2-6: Research Power Control Panels installed in Lancair aircraft instrument panel and console.

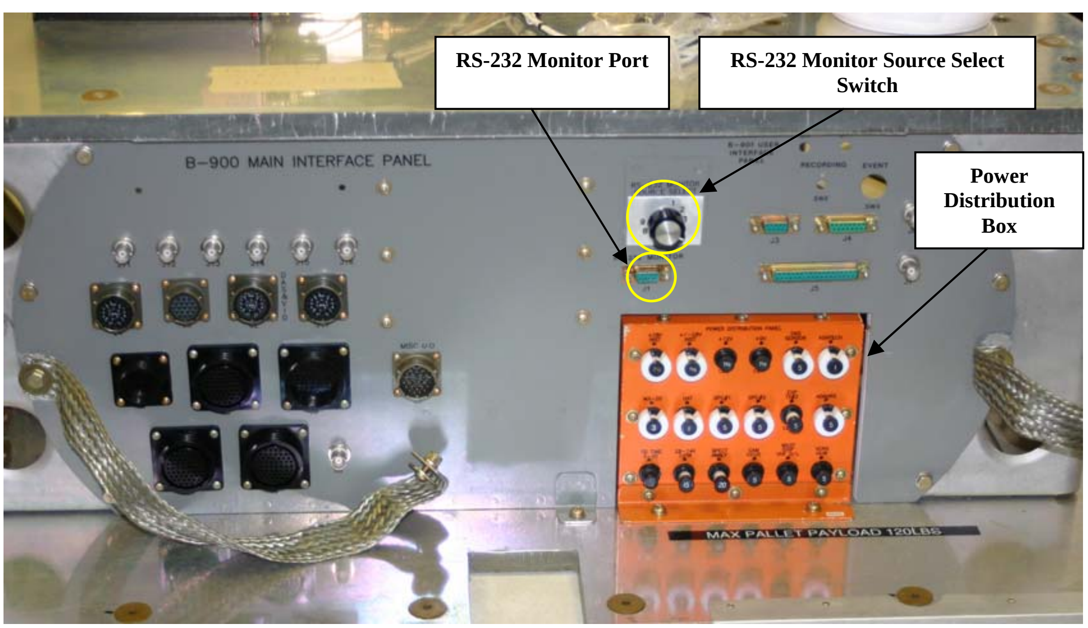


Figure 2-7: Aft research pallet front interface panel.

2.1.2 ARMS Electrical Interface

The ARMS installation package added electrical power capabilities beyond the basic research system. It provided the ability to monitor, collect, and record RF signal measurements and GPS data. The LaRC Lancair GABRS was configured to support the ARMS providing communication interfaces, such as RS-232 and GPIB, and additional electrical power to operate research system components.

The ARMS electrical power and communication interfaces are illustrated in Figure 2-8. The RF signal was obtained by using the secondary output of the NAV antenna splitter and connecting to the RF input of the spectrum analyzer. The NAV antenna was chosen because of its wideband characteristics which allowed the reception of a wide range of frequencies without the need to reconfigure the antenna input for the various frequency bands. The ARMS used the RS-232 Monitor Port located on the aft research pallet interface panel to access the aircraft's UPSAT GX-50 GPS receiver for acquiring position data. Figure 2-8 shows the RS-232 connected to the laptop computer serial port. A GPIB interface was used to connect the laptop computer to a spectrum analyzer to collect measurement data.

The 12 VDC power requirement for the laptop computer was provided by the basic research system's power distribution box, and an AK-551-18M 28 VDC to 14 VDC converter was installed to provide power for the ARMS spectrum analyzer. All outputs from the Power Distribution Box, 28 VDC, 14 VDC, and 12 VDC are circuit breaker protected, providing an additional means of individual circuit isolation and control.

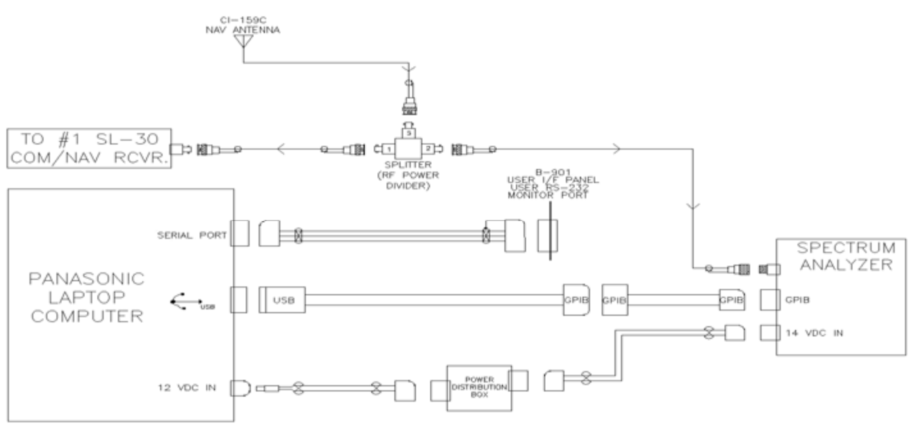


Figure 2-8: ARMS electrical power system and communication interfaces.

2.2 Mechanical

The mechanical requirements for the ARMS were to configure the aircraft to accommodate the installation of research equipment and to apply safety requirements, based on FAA regulations, to the new aircraft configuration. Analyses were performed to determine load conditions based on the addition of brackets, pallets, and equipment. The ergonomics of equipment operation during all phases of the flight envelope were taken into consideration during the design phase. The equipment was placed and aligned within the aircraft to best meet operation by the

researcher while still meeting the FAA regulations for design. Figure 2-4 shows the laptop computer and spectrum analyzer installed in the aircraft. NASA LaRC personnel completed all mechanical design, fabrication, and installation of the ARMS onto the Lancair aircraft.

Figure 2-9 shows an overall layout of the interior of the aircraft with the ARMS spectrum analyzer and laptop computer installed. Although the Lancair aircraft had an aft universal pallet for research equipment available it was not usable for the ARMS spectrum analyzer installation as its weight exceeded the pallet's forty pound maximum weight limitation. Therefore, the spectrum analyzer was mounted on the floor directly behind the pilot's seat (where a passenger seat is normally located). Existing seat belt hard points and other mounting points were utilized for installation purposes. In addition, a side pallet was designed and installed for mounting the laptop computer utilizing existing rear seat belt brackets and requiring the removal of the left passenger seat.

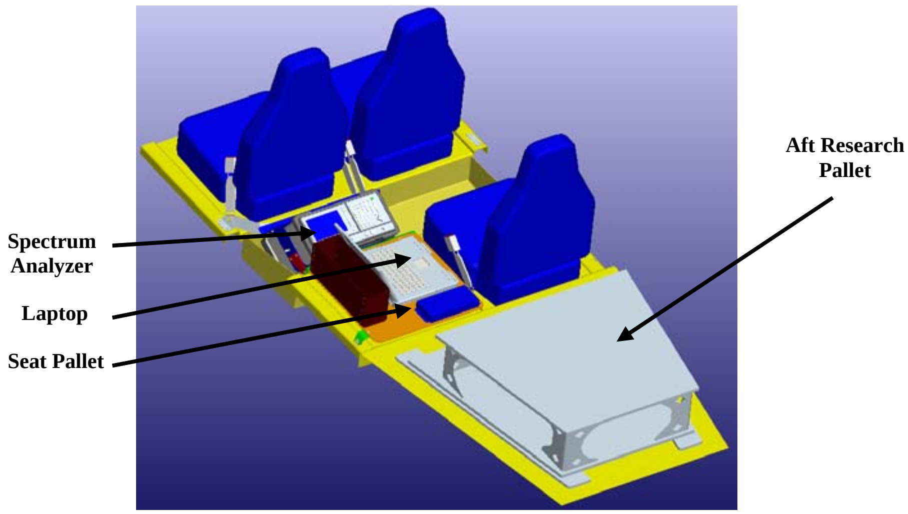


Figure 2-9: ARMS and aft pallet design layout in Lancair aircraft.

The side pallet structure for the computer was designed using static inertia load factors and conditions found in the Federal Aviation Regulations. Appendix B contains additional information addressing the airworthiness of the installation.

2.3 Software

This section describes the role of the software element of the ARMS. Requirements and development are discussed as well as software organization and capabilities.

2.3.1 Description

The "Aircraft Spectrum Monitor" software module provided automated instrument control, data acquisition, and data recording during a recent airport RF measurement survey. The software module continuously acquired and displayed spectrum analyzer, test, and GPS data, saving information in Microsoft Excel™ format.

2.3.2 Requirements and Development

Research objectives required the software to set and display spectrum analyzer and test parameters, acquire and display RF measurement and GPS data, apply calibrations to data in real time, and track and record data.   In addition, a list of selectable geographic end points defined by latitude and longitude coordinates, position, and distance to end point (runway reference coordinates) were provided.

Software and system development took place in the NASA LaRC High Intensity Radiated Fields (HIRF) Laboratory. Figure 2-10 shows a test bench setup including a laptop computer, a spectrum analyzer, a GPS receiver, a serial adapter, and a GPIB interface. Due to space limitations in the aircraft a laptop computer was selected to host the software. The laptop used the Microsoft Windows XP Professional operating system and Agilent's VEE Pro version 6.0 development environment. Figure 2-10 shows a GPS Simulator Unit (left), which includes an Apollo GX60 GPS receiver, manufactured by Garmin AT. It was used to simulate GPS receiver output data during software development and provided a data format similar to the Apollo GX50 GPS receiver in the Lancair aircraft. The laptop computer is shown connected to the GPS Simulator Unit via an RS-232 serial interface adapter (blue connector). The laptop computer was connected to a spectrum analyzer using a USB to GPIB interface adapter to control the spectrum analyzer and acquire measurement data. A working version of the software was demonstrated onboard the Lancair aircraft using its Apollo GX50 GPS receiver. Table 2-2 provides a list of the test bench hardware as well as aircraft installed hardware.

Figure 2-10: Test bench setup for ARMS software development.

Table 2-2: Development Test Bench and Aircraft Instruments and Hardware

Instrument and Hardware	Test Bench	Aircraft
Fujitsu P Series Lifebook	✓	
Panasonic CF-51 Toughbook laptop with serial ports	✓	✓
Garmin GPS 500 - GNS 530/530A Universal Aeronautical Communications Test Bench	✓	
Apollo GX60 GPS Simulator Unit	✓	
Apollo GX50 GPS receiver		✓
Port Authority 2 USB to Serial adapter	✓	
Agilent 82357A USB/GPIB interface	✓	✓
Agilent E4407 Spectrum Analyzer	✓	✓

During the RF measurement survey the "Aircraft Spectrum Monitor" software module continuously acquired the aircraft's current latitude and longitude positions. The end point data and current position data were utilized to calculate the distance between the aircraft's location and the designated end point. In the case of the airport RF measurements the end points were the GPS coordinates of the beginning of the runway for landing, also known as runway reference coordinates. The following equations were used to calculate this distance. Equation 2-1 simply

converts each position coordinate (a, b, c, and d) to decimal. Then Equation 2-2 uses the decimal values to calculate distance in degrees. Next, in Equation 2-3, degrees are converted to radians, which are then multiplied by the diameter of the Earth, giving the distance (meters) between the aircraft's current position and end point (runway reference coordinates).

Convert end point and current/starting point position coordinates, latitude and longitude degrees and minutes, to decimal using:

$$a,b,c,d_{[decimal]} = a,b,c,d_{[\deg rees]} + (a,b,c,d_{[\min utes]} / 60), \qquad \text{(Eq. 2-1)}$$

Where:

a = Starting point latitude,

b = Ending point latitude,

c = Starting point longitude,

d = Ending point longitude.

Calculate Distance (degrees) between current position and end point decimal values using:

$$Distance_{[\deg rees]} = acos(cos(a)*cos(b)*cos(d-c) + sin(a)*sin(b)). \qquad \text{(Eq. 2-2)}$$

Convert Distance (degrees) to Distance (radians) and multiply by diameter of Earth using:

$$Distance_{[meters]} = (Distance_{[\deg rees]} * (pi/180)) * 6378100. \qquad \text{(Eq. 2-3)}$$

2.3.3 Calibration and Data Files

The "Aircraft Spectrum Monitor" software module requires data from two previously recorded calibration files, one containing receive path losses and one containing antenna gains. The files must be in a three-column text format; column one is a list of frequencies, column two contains power losses/gains, and column three contains measured maximum receive power. The maximum receive power in the calibration file is for reference only. The frequencies and power losses/gains in the calibration files are applied to measured test data to correct for receive path loss and antenna gain. The test frequency range must be included within the calibration frequency range, but exact frequency matching is not required. The software determines the calibration values required for each test frequency by interpolation, using test and calibration frequencies, and power losses. The "Aircraft Spectrum Monitor" software module uses Equation 2-4 to automatically calculate isotropic power received at a point of measurement by applying the calibration data, receive path losses and antenna gains, to the test maximum receive power measured at the spectrum analyzer. All parameters are functions of frequency. Data calibration is discussed in detail in Section 5.2.

$$P_{Calibrated[dBm]} = P_{Rcv[dBm]} - (G_{Rcv\_path[dBm]}) + (G_{Ac\_ant[dBm]}), \qquad \text{(Eq. 2-4)}$$

Where:

$P_{Rcv[dBm]}$ = Power measured at the ARMS spectrum analyzer in connector,

$G_{Rcv\_path[dBm]}$ = Gain/loss in receive path. (If there is no preamplifier in the receive path, the magnitude is negative.)

$G_{Ac\_ant[dBm]}$ = Gain of aircraft antenna relative to an isotropic antenna. (If the aircraft antenna is not efficient or did not observe in the direction of the main beam, the magnitude may be negative. Section 5.2 addresses gain in more detail.)

Data is recorded in a user specified Excel file organized into worksheets and workbooks. The first two rows in the output Excel data file contain test and instrument parameters (Table 2-3). Date and Time refer to the file creation time. Section 4 Figure 4-2 gives an example of a populated output data file. The Excel data file includes a test

frequencies column, a calibrated data column, and an un-calibrated data column. The calibrated and un-calibrated columns, which comprise a 2-column data set, are repeated as a test continuously acquires and records more data. Associated with the two columns are several time related items of information: measurement or dwell time, GPS latitude and longitude coordinates, and distance to the end point or runway reference point. A data set and its associated data are recorded at the end of each measurement. An Excel worksheet may contain sixty data sets, and a workbook may include up to 24 worksheets. If a measurement occurs every 60 seconds, then a worksheet represents one hour, and a workbook twenty four hours or one day.

As the "Aircraft Spectrum Monitor" software module executes a test, GPS read errors and Excel write errors are recorded to file SpecMonError.txt in order to track system performance.

Table 2-3: Test and Instrument Information in First Two Rows of Data File

Parameters	Description
Date and Time	File creation time (hours, minutes, seconds)
Start and Stop Frequency	Defines test frequency band (MHz)
SA resolution bandwidth	Spectrum analyzer setting (dBm)
SA sweep time	Spectrum analyzer setting (seconds)
SA reference level	Spectrum analyzer setting (dBm)
SA attenuation	Spectrum analyzer setting (dBm)
Calibration file names	Two files containing receive path and antenna calibrations
End Point latitude and longitude	Airport runway coordinates

2.3.4 Organization

The "Aircraft Spectrum Monitor" module window is divided into two main sections (Figure 2-11). The "Operations Menu" section includes a list of operations for setting spectrum analyzer and test parameters and starting and stopping a test (Table 2-4).

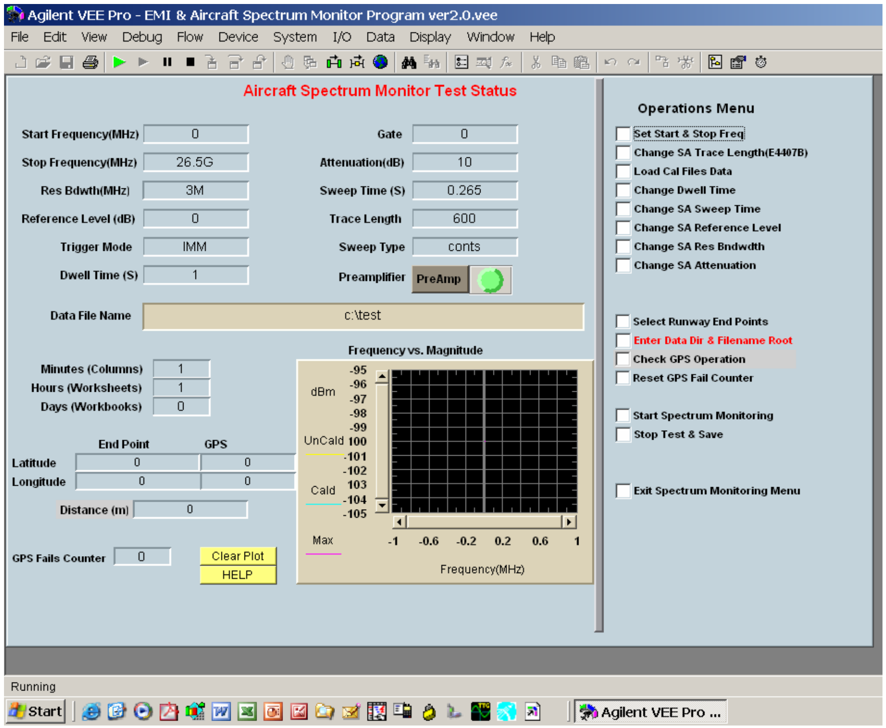


Figure 2-11: "Aircraft Spectrum Monitor" module window.

Table 2-4: "Aircraft Spectrum Monitor" Operations

Operations	Description
Set start & stop frequency	Define test frequency band
Load Cal Files Data	Enter two file names that include calibration data
Change Dwell Time	Change the length data measurement time
Change SA Sweep Time	Change spectrum analyzer sweep time
Change SA Reference Level	Change spectrum analyzer reference level
Change SA Res Bandwidth	Change spectrum analyzer resolution bandwidth
Change SA Attenuation	Change spectrum analyzer built-in attenuation
Enter Data Dir and Filename Root	Enter the full path and filename for output Excel data file
Select Runway End Points	Select GPS coordinates from a list of airport locations
Check GPS Operation	Check GPS communication status
Reset GPS Fail Counter	Set the counter back to 0
Start Spectrum Monitoring	Begin automated data acquisition and create a data file
Stop Test and Save	End test and save data to an Excel file
"Exit Spectrum Monitoring Menu"	Close the "Aircraft Spectrum Monitor" module's window

The "Test Status" section of the "Aircraft Spectrum Monitor" window displays test and spectrum analyzer parameters, a graph of measured data, and GPS coordinates. The fields reflect changes made using the operations in the "Operations Menu". The fields displaying the spectrum analyzer parameters reference level, sweep time, and resolution bandwidth may be different than values entered using the menu operations. Because these parameters are linked internally within the spectrum analyzer, one parameter can automatically change another.

Below the test parameter fields the "Data File Name" field displays the selected output data file name. Data is written to this file at the end of each dwell time, creating worksheets and workbooks as needed. The file name can be changed using "Enter Data Dir & Filename Root" in the "Operations Menu".

The column in the left middle of the "Test Status" section contains fields for Minutes (Columns), Hours (Worksheets), and Days (Workbooks). These are used to display testing duration in units of time which relate to the Excel workbook organization. As an example, a one to one relationship exists if the test dwell time is one minute. The Minutes (Columns) field will display the number of minutes that have transpired since beginning the test, which then relates to the number of two-column data sets written to an Excel worksheet. Using this example, every worksheet may contain up to sixty one-minute data sets corresponding to approximately sixty minutes test time or one hour. Every workbook may contain as many as twenty four hours or worksheets equivalents displayed in the Hours (Worksheets) field. Of course, if the test dwell time is not equal to one minute then the relationship between the Excel workbook organization and the time definitions changes accordingly. The number of days or workbooks is not limited by the software and is displayed in the Days (Workbooks) field.

The data graph in the lower portion of the "Test Status" section is used to display real time measurements as frequency (MHz) versus measured amplitude (dBm). The calibrated data with path and antenna losses applied are displayed in blue, and the un-calibrated data acquired directly from the spectrum analyzer are shown in yellow. Also, a maximum hold trace is displayed in purple. Plots can be cleared as needed using the "Clear Plot" button.

The data fields, Latitude and Longitude, End Point and GPS, are located in the lower left of the window. These fields give the End Point GPS coordinates and the real time GPS coordinates. GPS data is acquired and updated continuously and compared to a selected end point. The distance in meters between current position coordinates and end point coordinates is calculated using the current GPS position data and the end point data. The calculated distance is displayed in the Distance (m) field. Section 5 uses the Distance values (Distance-to-Runway) to calculate altitude. The GPS failure counter tracks the number of times that serial communication produces an error. The software handles the error, re-establishing communication and increments the counter.

3 Electromagnetic Interference (EMI) Aircraft Testing

An aircraft-level electromagnetic interference (EMI) test was performed on the LaRC Lancair Columbia 300 aircraft configured with the ARMS measurement test instrumentation. This EMI testing was conducted by the LaRC's Systems Integration and Testing Branch. The purpose of the test was to ensure flight safety by assessing the EMI impact of the flight research system on the aircraft's communication and navigation systems. The research systems' radiated emissions were measured using a spectrum analyzer connected to the aircraft's NAVCOM receivers' antenna ports. The measured research system noise was verified, and the noise sources were identified. Communication radio checks were performed to determine the impact of the research system noise on suspect communication receiver channels. All COM/NAV suspect channels were tested during the instrument check flight (ICF) for an in-flight assessment of their impact to the communication and navigation systems. Suspect COM channels are channels that demonstrated interference during the communication radio check. Suspect NAV channels are channels with frequencies less than or equal to half of the radio's channel separation to any research system noise measured.

3.1 EMI Test Setup

As shown in Figure 3-1, the aircraft was located outside the LaRC hangar on an engine run-up ramp, and the EMI test equipment was located in a NASA van parked near the aircraft. A portable ground power unit powered the Lancair aircraft systems, research systems, and the EMI test equipment.

The Lancair aircraft was in a research flight configuration for this test, with the following research equipment installed and operational: laptop computer, spectrum analyzer and 28V to 14V DC-DC converter. The laptop computer was running the research software during the EMI test.

Figure 3-1: Lancair EMI test setup on the NASA LaRC Run-Up Ramp.

Figure 3-2 provides a block diagram of the EMI test setup. The distinction between the Lancair's aircraft and research systems shown in Figure 3-2 represents a physical and electrical isolation between the two systems for flight safety purposes. The intentional distinction between the two systems is used to isolate the research system's radiated emissions during the EMI test. An RF cable was connected between the spectrum analyzer and the appropriate COM/NAV antenna port for each of the measurements performed. The bias-tee shown in Figure 3-2 is an RF hardware device that allows the GPS radio to be connected simultaneously to the GPS antenna and the spectrum analyzer while still providing DC power to the GPS antenna's preamplifier. The bias-tee blocks the DC bias from the spectrum analyzer, which has an AC only input.

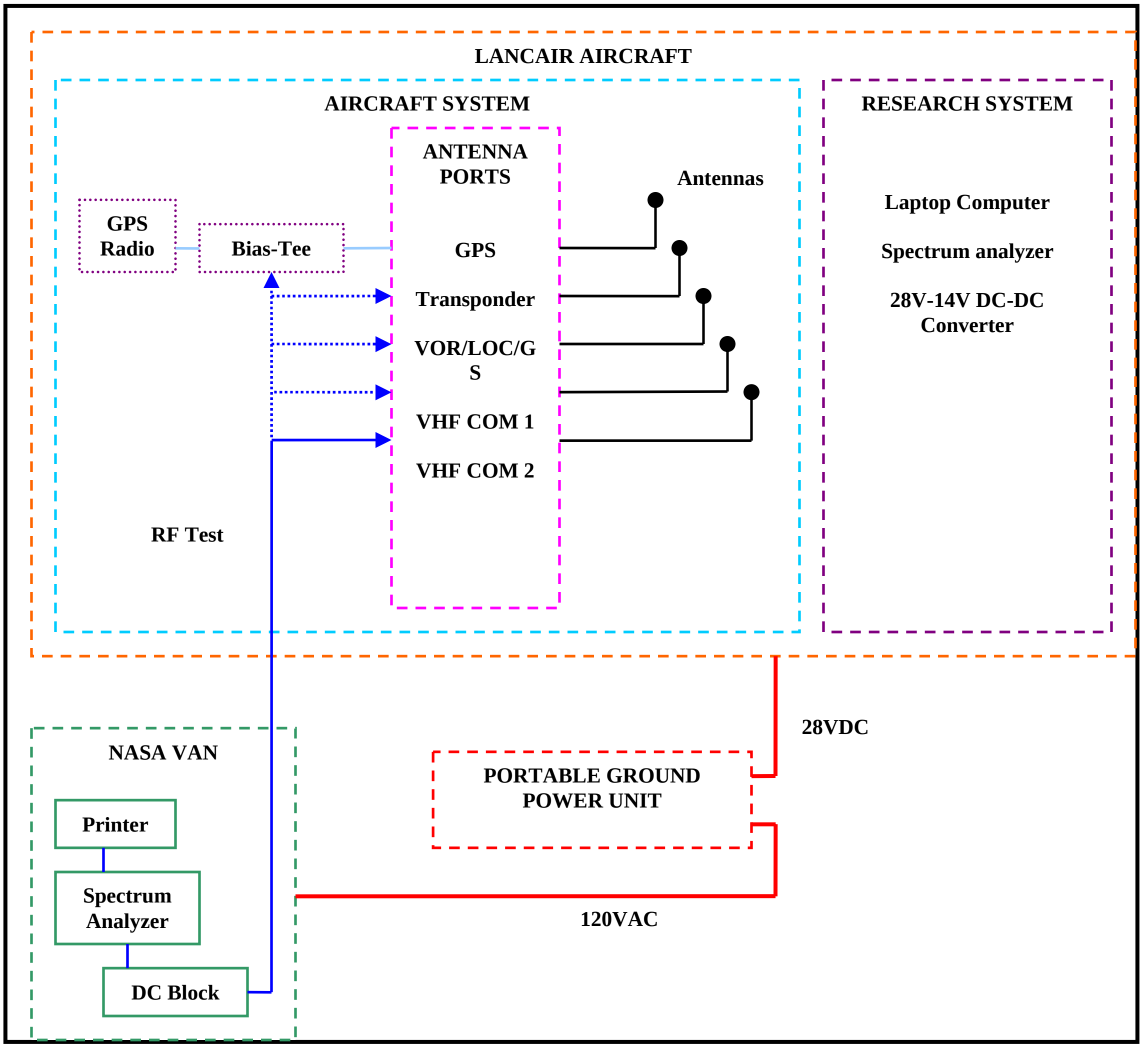


Figure 3-2: Lancair aircraft EMI test setup.

3.2 EMI Testing Performed

The EMI testing on LaRC's Lancair general aviation aircraft is a three part process consisting of spectrum analyzer measurements, ground radio checks and flight radio checks. The following Lancair COM/NAV radio systems were tested: VOR/LOC, GS, GPS, transponder, Marker Beacon (MB), VHF COM 1 and VHF COM 2. The marker beacon was only tested during the instrument check flight; the special adaptor needed to connect the Lancair's marker beacon antenna to the spectrum analyzer was not available at the time of the EMI test.

3.2.1 COM/NAV Antenna Port Spectrum Analyzer Measurements Scans

The spectrum analyzer measurements were made at the antenna port of each COM/NAV receiver. This is illustrated in the test setup drawing shown in Figure 3-2. The antenna port measurements performed and the frequency band for each are listed in Table 3-1.

Table 3-1: Receiver Antenna Port Measurements

Frequency Range	Receiver Antenna Port Measured
108 MHz – 118 MHz	VOR/LOC 1
328 MHz - 335 MHz	GS 1
1565 MHz – 1585 MHz	GPS
1029.8 MHz – 1030.2 MHz	Transponder
118 MHz – 138 MHz	VHF COM 1
118 MHz – 138 MHz	VHF COM 2

The spectrum analyzer measurements consist of three scans (background, noise and source identification) performed sequentially for each COM/NAV radio system. The background scan provides a baseline measurement of emissions from the local environment and the aircraft's systems. A background scan was performed with the aircraft's equipment powered on and the research equipment powered off to identify the background signals that exceeded the noise measurement threshold. The noise measurement threshold value used for each receiver was derived from the receiver's sensitivity. Next, with both the aircraft and research systems powered on, noise scans were made to identify signals that exceeded the noise measurement threshold and were not present during the background scans. These noise signals were investigated during the source identification scans to identify the research system source and ensure that they were not periodic background signals. Results of the scans are presented in Section 3.3.

3.2.2 Communication Radio Checks

With all of the aircraft and research equipment powered on, both communication radios were tuned to suspect channels on both sides of the measured noise signals. The suspect channels were checked to determine if the noise signals caused the communication radios to exceed the radio's squelch threshold or produce audible noise with the radio's squelch disabled. The squelch circuit only allows received signals at a specified strength to be passed through the aircraft audio system. A pattern noise scale of PN0 – PN10 is used to characterize the audible noise heard during the communication radio check. A portion of the pattern noise scale used is listed in Table 3-2. The noise signal sources were powered on and off to confirm the interference from the research system and to validate the findings of the source identification scans.

Table 3.2: Communication Radio Check Pattern Noise Scale

Pattern Noise Type	Characterization
PN0	No audible noise
PN1	Noise is barely audible and channel is usable
PN5	Audible noise is barely annoying, but channel is usable
PN10	Audible noise is excessive, and channel is unusable

3.3 EMI Testing Results Summary

Results of the communication receiver EMI tests indicated that the research system did not produce any emissions that exceeded the noise measurement threshold, therefore no ground or flight communication radio check was required.

Results of the navigation receiver EMI tests indicated that the research system did not produce any emissions that exceeded the noise measurement threshold for the glideslope, transponder, and VOR/LOC navigation systems. No interference was detected during the marker beacon check performed during the instrument check flight.

Narrowband, un-modulated noise was measured from the research system's laptop and spectrum analyzer. The noise from these systems was outside the GPS Commercial Course/Acquisition C/A-Code's 2 MHz bandwidth, but within the GPS Precision P-Code's 20 MHz bandwidth. The noise signals measured during the GPS scans were not expected to impact the GPS system, because the GPS is a broadband, spread spectrum receiver inherently immune to most narrowband, un-modulated noise. However, the GPS system was checked during the instrument check flight to assess the impact of these noise signals on the GPS system: no impact was measured.

4 Flight RF Survey: Measurement Method

All ARMS measurements discussed in this paper were made from a Lancair aircraft on approach to an airport runway. The measurement method is discussed, including airport approaches, test operation and procedure, measurement and instrument parameters, and data collected.

4.1 Airport Approaches

Federal Aviation Administration (FAA) Instrument Approach Procedures (IAP's) were used for each airport included in the aerial RF measurement survey. The following types of IAP's were used for approaches and landings: Instrument landing system (ILS, which includes GS and LOC), VOR and GPS. The primary focus of the survey was the accurate measurement of LOC and GS signal levels using ILS IAP's. GPS and VOR approaches were also flown to provide an alternative aircraft glidepath for data comparison to ILS IAP's. VOR approaches were not available at all the airports.

Figure 4-1 (a) and (b) illustrate ILS, GPS, and VOR approach paths. The gray region surrounding the line indicating ILS approach path is known as the "feather". An aircraft located in this region is on course for an airport landing. A GPS approach requires that a specific altitude be achieved at each waypoint, so the descent pattern is often interpreted to resemble a step down approach.

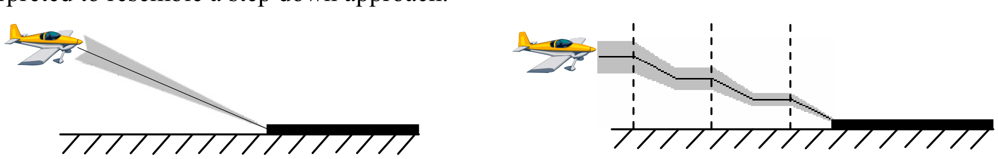


Figure 4-1: (a) ILS approach path. (b) GPS/VOR approach path.

Data was collected during either “long range” (25 miles) or “normal” (3 miles) approaches to a designated airport, depending on the test objective. During “long range” approaches (ILS only) the objective was to determine the distance from the airport at which the aircraft begins to receive the target navigational signal. Using normal approaches (ILS, GPS, and VOR) the test objective was to collect data beginning at the interception point of the navigational signal as specified in the IAP.

4.2 Measurement Parameters

During typical ILS, GPS, and VOR IAP’s, RF survey data (LOC, GS, and VOR) were measured using the aircraft’s NAV antenna over a broad band of frequencies (30 MHz to 1000 MHz). Additionally, LOC and GS RF signal measurements were made during ILS approaches using narrower frequency ranges. Table 4-1 lists the measurement frequency ranges and categorizes the test variables and spectrum analyzer parameters by IAP type and measurement type. The spectrum analyzer parameters were adjusted according to the strength of the received signal during broad band tests. For instance, if the signal measurement was particularly strong with a low noise floor, then the reference level was lowered and the resolution bandwidth was increased. The broad band measurements include ILS and VOR signal data, but no GPS signal data as GPS signals are outside the broad band frequency range. The narrower frequency ranges selected were dependent on the airport’s LOC or GS channels. These frequency ranges were created by applying 2 kHz to either side of the tunable LOC and GS channels. The narrow band measurements for the LOC and GS signals were used to validate the broad band data, as well as lower the measurement noise floor (an added benefit for identifying lower signal levels). Since the testing focused on the LOC and GS signals, no VOR narrow band data was collected.

Table 4-1: Test Variables and Spectrum Analyzer Parameters

IAP Type	Msmt Type	Frequency Ranges (MHz)	Resolution Bandwidth (kHz)	Dwell Time (sec)	Sweep Time (ms)	Atten-uation	Reference Level (dBm)	Trace Length
ILS/VOR/GPS	Broad band (ILS/VOR)	30-1000	100 300	1 2	.125 19.41	0	-10 -20	1942
ILS LOC	LOC	109.898-109.902 110.098-110.102 109.098-109.102 110.898-110.902 110.698-110.702	.030	2	485	0	-20	401
ILS GS	GS	333.796-333.800 334.398-334.402 331.398-331.402 330.798-330.802 330.198-330.202	.030	2	485	0	-20	401

4.3 Test Procedure

All RF measurement survey tests began with the aircraft on the flight ramp. Each tests included instrumentation checks, spectrum analyzer and test setup using the “Aircraft Spectrum Monitor” software, and data collection and recording. The test software operations are described in detail in Section 2.3. Test personnel included one pilot and one researcher. The researcher, seated in the right rear seat next to the laptop computer (Figures 2-4 and 2-9), operated the equipment. While on the flight ramp the pilot started the aircraft engine, turned on the aircraft equipment power and made the proper flight clearance arrangements with the tower. While still parked on the ramp the following test procedure was implemented:

1. Turn on the research power on center console (Figure 2-4).
2. Power up the Panasonic CF-51 Toughbook Laptop and the HP 4407B SA.
3. Complete SA calibration.
4. Open the "Aircraft Spectrum Monitor" software (Section 2.3).

If all the ARMS equipment is working properly, the Lancair proceeds to take off.

5. View parameters in "Test Status" and make necessary changes.
6. Enter appropriate parameters as needed under the "Operation Menu".
   - Set Start & Stop Frequency
   - Change SA Trace Length
   - Load Cal Data Files
   - Change the Dwell Time
   - Change SA Sweep Time
   - Change SA Reference Level
   - Change SA Resolution Bandwidth
   - Change SA Attenuation
   - Select Runway End Points
   - Enter Data Dir & Filename Root
   - Check GPS Operation
   - Start Spectrum Monitoring - begin measurement when the pilot gives verbal cue that the aircraft is making a turn to intercept the intended NAV signal.
   - Stop Test & Save - end measurement after arriving at the runway destination, when the pilot either completes a successful approach and landing or executes a "missed approach".

4.4 Data Files

Each airport approach resulted in measurements and test setup parameters recorded to an Excel file. The file nomenclature was based on the airport designated abbreviation (AAA), runway number (##), IAP type (XXX), and a special field (YYY) to indicate narrow band (NB) and long range (LR) measurement setups and approach distances (Table 4-2). The file nomenclature (YYY) listed in the "Special" column was used only in file names with ILS approach data. To expedite test operation, data file names were setup prior to flights. "Airport" and "Runway Number" data contained in Table 4-2 is for illustrative purposes only.

Table 4-2: Excel File Naming Nomenclature (AAA_##_XXX_YYY)

Airport (AAA)	**Runway Number (##)**	**IAP Type (XXX)**	**Special (YYY)**
ABC	02	ILS	LR
XYZ	07	GPS	NB LOC
	10	VOR	NB LOC LR
	22		NB GS
			NB GS LR

Data file size depends on the approach distance and time duration of test and data collection. Figure 4-2 is an example of an Excel worksheet from a data file. The first column of the worksheet is populated with spectrum analyzer measurement frequencies. The next columns contain measurement data organized in 2-column data sets containing a calibrated column ("Cald") and an un-calibrated column ("Uncald"). Associated with each data column are "Timestamp", "Latitude", "Longitude", and "Distance" fields.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Date	Time	Start Freq	Stop Freq	Res Bndw	Swp Time	Ref Lvl	Atten	Facility	Cable Cal	Chmbr Cal	End Pt. Lat	End Pt. Long
2	07:11:05	15:55:14	30.0000	1000.0000	0.3000	0.0194	-20.0000	0.0000	Chamber A	C:\	C:\ Antenn	37 N	76 W
3	Timestamp	15:55:16	15:55:16	15:55:18	15:55:18	15:55:20	15:55:20	15:55:22	15:55:22	15:55:24	15:55:24	15:55:26	15:55:26
4	Latitude	36 N	36 N	36 N	36 N	36 N	36 N	0.0000	0.0000	37 N	37 N	37 N	37 N
5	Longitude	76 W	76 W	76 W	76 W	76 W	76 W	0.0000	0.0000	76 W	76 W	76 W	76 W
6	Distance (m)	17700	17700	17650	17650	17580	17580	17580	17580	17430	17430	17360	17360
7	Freq(MHz)	Cald(dBm)	UnCald(dBm)										
8	30.0000	-114.2740	-79.7540	-114.4320	-79.9120	-113.0670	-78.5470	-115.7880	-81.2680	-110.1980	-75.6780	-113.6120	-79.0920
9	30.4997	-115.2220	-80.6420	-116.9330	-82.3530	-117.0770	-82.4970	-115.2770	-80.6970	-114.2470	-79.6670	-115.9030	-81.3230
10	30.9995	-117.1769	-82.5370	-116.3559	-81.7160	-117.0459	-82.4060	-115.5529	-80.9130	-115.0249	-80.3850	-116.3839	-81.7440
11	31.4992	-115.1280	-80.4580	-115.9220	-81.2520	-115.1770	-80.5070	-116.8070	-82.1370	-117.0740	-82.4040	-116.5610	-81.8910
12	31.9990	-110.1106	-75.4130	-111.0336	-76.3360	-111.6196	-76.9220	-113.2766	-78.5790	-109.9736	-75.2760	-111.2666	-76.5690
13	32.4987	-116.0965	-81.3820	-119.3595	-84.6450	-119.2965	-84.5820	-117.9835	-83.2690	-116.9285	-82.2140	-117.6285	-82.9140

Figure 4-2: Excel data file example.

4.5 Log Sheets

A timestamp and additional information was recorded in a test log book (Table 4-3) to correlate the operator's notes with the data in Excel files. This information relates the columns of data at a given coordinate to the test time. On approaching an airfield, information, such as altitude, airspeed, distance-to-runway, and valid approach signal reception was acquired from the pilot, as well as the aircraft cockpit compass system and software status window. Time was taken from the software in order for the information to correspond directly with the automated data file time entries.

Table 4-3 is an example of log entries for one approach. The first entry in the "Time" column specifies the time the data file was created as is designated in the "Comments" column. The second entry in the "Time" column specifies when the data collection was started. Comparing the first and second time entries indicates a delay between file creation time and beginning the actual data collection process. The delay is expected since data collection is not started until the aircraft arrives at a specific distance from the runway. The additional entries in the "Time" column relate to the other table entries as they occurred. The altitude and airspeed were recorded from the aircraft altimeter and airspeed indicator. The next column, "Distance To Runway" was recorded from the test software's "Distance" field displayed in the "Test Status" section of the "Aircraft Spectrum Monitor" window. "Uncal" or signal level was recorded from the spectrum analyzer display. Subsequent entries "LOC Lck" or localizer lock, "GS Lck" or glideslope lock, and "Enter Feather" are derived from the cockpit Horizontal Situation Indicator (HSI) display. When the aircraft received valid LOC and GS signals, the time was logged as entering the "feather".

Table 4-3: Test Log Example

Time	**File Name**	**Altitude (feet)/ Airspeed (knots)**	**Distance To Runway (meters)**	**Uncal (dBm)**	**LOC Lck**	**GS Lck**	**Enter "Feather"**	**Comments**
3:48	AAA_##_XXX_YYY							Setup and create file
3:55								Start data collection
3:55		2000/130	16707					
3:56		2000/135	11728	-60.0	x	x	x	

5 Flight RF Survey: Results and Analysis

This section presents data collected by ARMS during a single ILS landing approach at one airport. The data is considered representative of the RF environment at all the airports included in the RF measurement survey. A data analysis discusses aircraft NAV and measurement frequency bands, as well as other observed RF signals. Calibration dependencies are discussed regarding antennas, in-band and out-of-band measurements, and cable losses. Particular aircraft and transmitter scenarios are explored with methods for applying calibrations.

The ARMS measured and collected data during 43 landing approaches at four different airfields. Three navigation systems, ILS, GPS, and VOR, were used during the landing approaches depending on the IAP selected. The data contain ILS localizer, ILS glideslope, and VOR measurements. GPS coordinates were collected and recorded to correlate with measured data.

5.1 Full RF Spectrum Data for a Typical ILS Flight Approach

The typical ILS approach and landing captured thirteen minutes of measurement data including a 250 second taxi from the runway to a hangar. Data collection resulted in a MS Excel workbook with seven worksheets, each with up to 46 columns of data. A sample of the MS Excel output data worksheet is shown in Figure 4-2. As shown in this example, the "Cald" column data requires further corrections to adjust the measurements beyond the calibrations (receive path losses) that were applied at the time of the flight survey. The measurements are also subject to the directivity and efficiency characteristics of the aircraft's navigation antenna. The application of antenna calibrations is needed in order to utilize quantitative data for any purpose other than to determine the presence or absence of high-level signals. A discussion of antenna calibration and application is provided in Section 5.2. To protect potentially sensitive data specific airport locations and quantitative data levels are not given in this paper.

The data images presented show signal amplitude versus frequency and time during a single in-flight RF measurement survey conducted during a typical approach and landing. The data are scaled using a Matlab full-color map to produce 2D plots representing 3D images, similar to a "relief" map of terrain data. The color-bar to the right of the plot represents the amplitude of the signal received. The low-end (dark blue) of the measured spectrum represents the noise floor.

Below each data image, there is an altitude plot with the same time-scale. The y-axis is altitude represented in feet and the x-axis is time represented in seconds. Altitude was calculated using Distance-to-Runway data recorded by the "Aircraft Spectrum Monitor" software module. Since the ILS approach angle was constant for the entire data collection period a simple geometry calculation was used to determine altitude.

Figure 5-1 illustrates the entire frequency range (30 MHz to 1000 MHz) of data collected for a single in-flight RF measurement during a typical approach & landing. Later figures divide and plot the full spectrum data into smaller frequency ranges for further analysis.

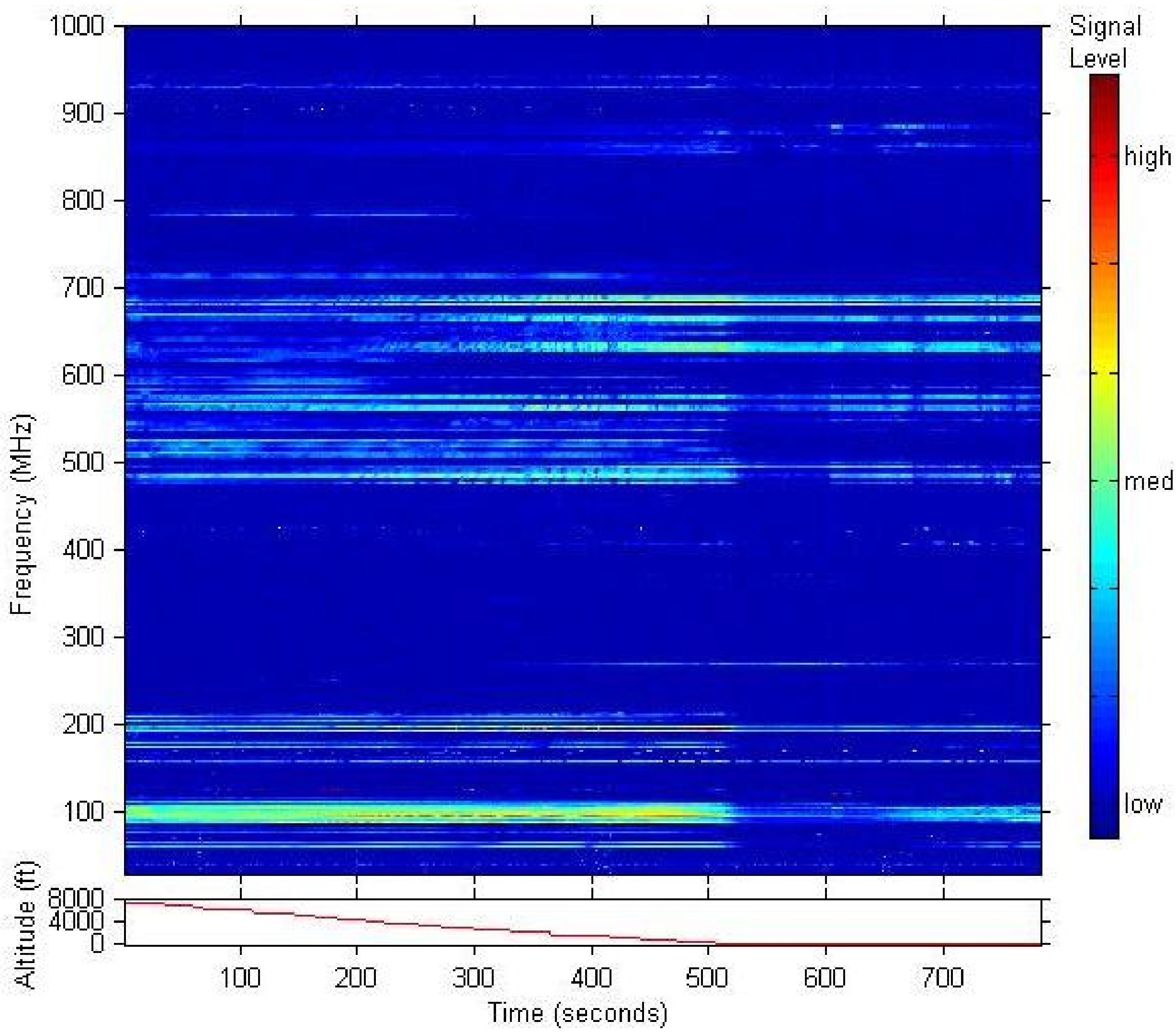


Figure 5-1: In-Flight Spectrum Environment for 30 to 1000 MHz.

Table 5-1 groups the RF spectrum from 30 MHz to 1000 MHz into 10 allocation bands and summarizes the various applications within each band. This frequency range corresponds to the data shown in Figure 5-1. A popular reference book, "Wireless Spectrum Finder", was used to obtain RF band summary information used in Table 5-1, and subsequent tables in this report [ref. 8]. A more comprehensive compendium of U. S. RF allocation information, policies, standards and procedures may be found in the NTIA "Redbook" [ref. 9].

Table 5-1: Frequency Allocation Summary for 30 – 1000 MHz

Frequency Band (MHz)	Use Summary
30 – 88	Cordless Phones, Baby Monitors, Amateur radio, TV Channels 2 to 6
88 – 108	FM Broadcast Radio
108 – 138	Aeronautical Navigation and Communication (ILS LOC, VOR)
138 – 174	Civil Air Patrol, U. S. Coast Guard, ATC, Navy, Local Government., LoJack, Weather Radio, Emergency Position Indicating Radio Beacons (EPIRB), Amateur radio
174 – 216	TV Channels 7 to 13
216 – 400	U.S. Military. Maritime Telcom, Space Surveillance, ILS Glideslope, Amateur
400 – 470	Meteorological, Space, Missile Defense, FRS, GMRS, Amateur, Aero. Telephone
470 – 824	TV Chan. 14 to 67, Medical Telemetry, wireless mics, Pub/Priv Mobile svcs, Radars
824 – 901	Cellular Handsets & Base Stations, GTE AirFone, Private Land Mobile
901 – 1000	Cordless Phones, ISM, LMS, ITS, Pub/Priv Mobile svcs, Fixed, U.S. Govt., Aero.

Figure 5-1 and Table 5-1 reveal significant information about the RF spectrum in a typical suburban environment. Some RF bands are much more heavily used than others. For example, it is readily evident that the FM Broadcast Radio band and the Television bands are "always on", whereas most other RF bands are more intermittent. Note how most signal levels decline significantly upon landing (about 500 seconds into the data). The higher signal levels measured before landing shows that virtually all signals are more easily detected with the receive antenna is at higher altitudes. At approximately 500 seconds the measured signal strength becomes significantly lower, because the aircraft has landed. No excessively high signal levels were obtained in this data set. The spectrum analyzer attenuation was set to zero and the internal preamplifier was off to prevent overloading the spectrum analyzer input and to insure accurate data measurement. A very high-level signal could overload the spectrum analyzer input, which would result in a data image with "red" signal level data and associated harmonics at frequency multiples.

Figure 5-1 is too small to show the actual measurement data resolution of 500 kHz steps every 2 seconds. It is helpful to separate Figure 5-1 into ten band-segments, and expand each one to reveal more detail in each RF frequency band. This is done in Figures 5-2 through 5-12 where a data resolution of 500 kHz and 2 seconds is utilized.

Spectrum analyzer data (as shown in Figure 5.1 and subsequent plots) provide information about observed frequencies and amplitudes; however, it is often not possible to identify the source of a particular signal solely by its frequency. RF spectrum regulations often allow multiple radio services to share RF spectrum based upon geographic location, licensing and transmit power. RF transmitters are sometimes operated outside their authorized allocations due to operator error, equipment malfunction or even operator intent. In order to investigate the observed signals, field evaluations were performed using a handheld scanner near select airports surveyed with the ARMS. The handheld scanner (ICOM IC-R20) was set to decode continuous wave (CW), amplitude modulation (AM), lower and upper side bands (LSB, USB), frequency modulation (FM), and wide frequency modulation (WFM). Comparing the field evaluation data to the RF survey data images and frequency allocation information and tables, it is possible to further identify sources of particular signals during post-flight investigation. The findings are summarized in the following subsections for selected frequency bands.

5.1.1 30 MHz to 88 MHz

The 30 MHz to 88 MHz RF band is used for television broadcast, amateur radio, public safety, federal government, military and non-commercial FM radio. Table 5-2 provides a summary of frequency allocations for this RF band. Table 5-3 contains a list of frequencies acquired during a field evaluation. Some interesting features in the data of Figure 5-2 include the dominance of the television channels in the band, and the presence of signals that appear to be random noise at many frequencies for very short bursts of time. With the exception of 40 MHz, most signal levels decline significantly with altitude (upon landing, about 500 seconds into the data). The data image in Figure 5-2

shows that some signal level colors fluctuate over time. The fluctuations indicate receive signal reductions that may be due to line-of-site shading by the airplane wings and fuselage or terrain reflections. The shading may to be responsible for occasional reductions in the 60 MHz to 66 MHz (television channel 3) received signal. The aircraft antenna used for this ARMS flight is not expected to be very directional in this RF band.

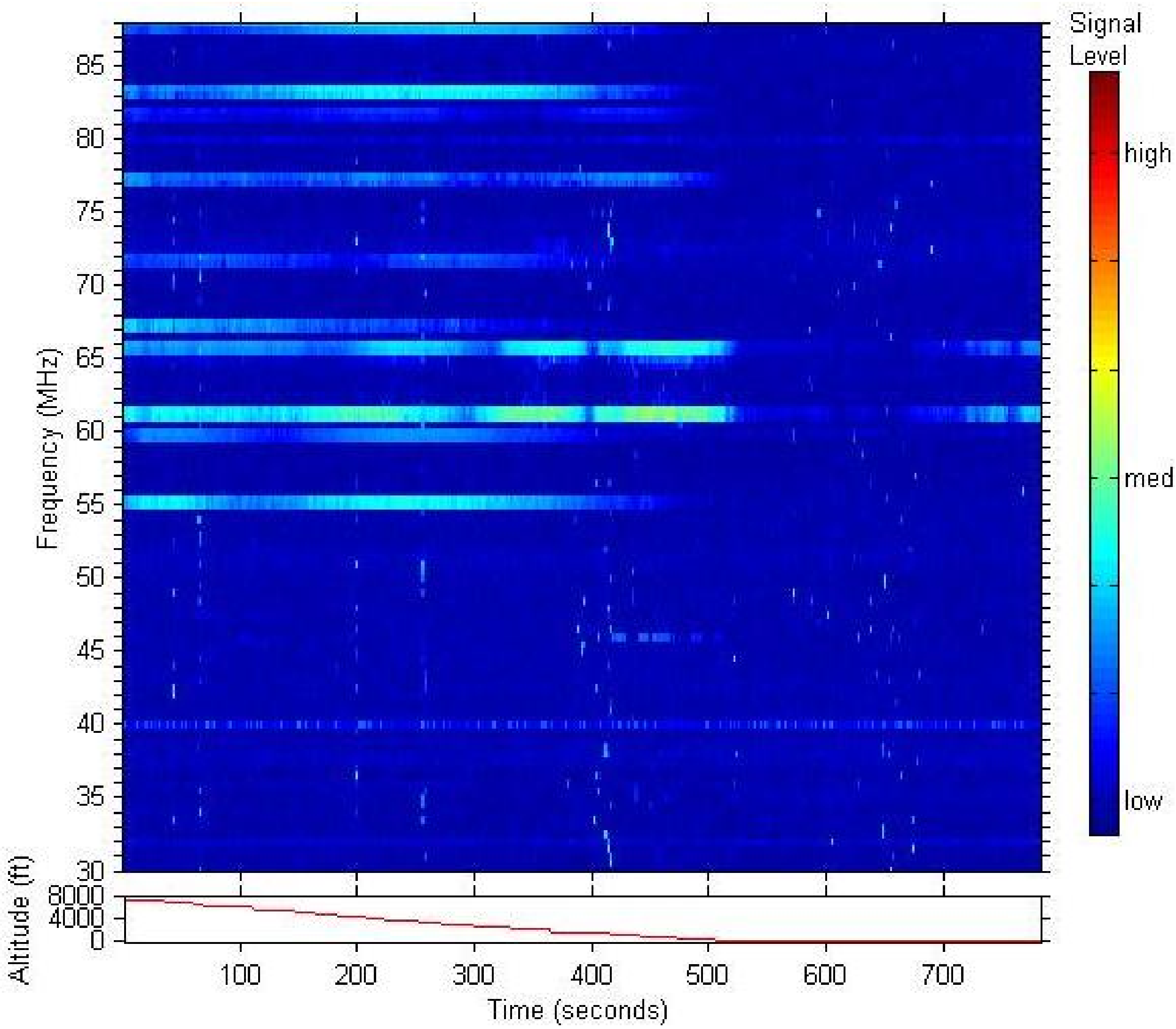


Figure 5-2: In-Flight Spectrum Environment for 30 to 88 MHz.

Table 5-2: Frequency Allocation Summary for 30 to 88 MHz

Frequency (MHz)	Use
32	Fixed Mobile. Federal agency and Army, Navy, Marine, and Air Force
39 – 40	Land Mobile. Public Safety Users. Largely devoted to police radio. Fixed Mobile. Federal Agency and Military (40 MHz)
46	Land Mobile Cordless Phones (43.69 – 46.6 MHz)
52	Amateur Radio (50 – 54 MHz)
54 – 60	TV Channel 2
60 – 66	TV Channel 3
66 – 72	TV Channel 4
72– 76	Public Mobile, Public/Private Land Mobile, Aeronautical Marker Beacon, Radio Astronomy, Remote control for model airplanes & boats
76 – 82	TV Channel 5
82 – 88	TV Channel 6
87.9	Noncommercial FM radio

Table 5-3: Field Evaluation of Signals Using a Handheld Scanner for 30 to 88 MHz

Frequency (MHz)	Modulation Setting	Date	Description of Audible Signal
32.00	WFM	10/10/06	“Clicking” sound. Periodic-1 time per second.
40.00	WFM	10/10/06	Intermittent tone: ~800 Hz. Unidentified harmonics of broadcast TV station.
46.00	WFM	7/17/06	Intermittent tone: ~800 Hz. Unidentified harmonics of broadcast TV station.
55.00	WFM	10/10/06	Intermittent, unidentified harmonic of FM Radio station
65.75	WFM	10/10/06	TV Channel 3 audio

5.1.2 88 MHz to 108 MHz

The 88 MHz to 108 MHz RF band is used exclusively for commercial FM radio broadcast. As illustrated by Figure 5-3 this RF band is fully utilized. Another feature is significant reduction in received signal levels at ground level (after 500 seconds). The data image in Figure 5-3 shows that some signal levels fluctuate over time. The signal level reductions may occur due to line-of-site shading by the airplane wings and fuselage. As stated previously, the aircraft antenna used for this ARMS flight is not expected to be very directional in this RF band. Also, because the terrain was somewhat reflective in this RF band, ground reflected signals will phase-cancel with the direct signals at periodic locations. These pattern shading and ground reflection effects may explain the periodic signal level changes, particularly in the 96 MHz received signal. No field evaluations were performed in this band as the signals are well known and can be identified in the data image.

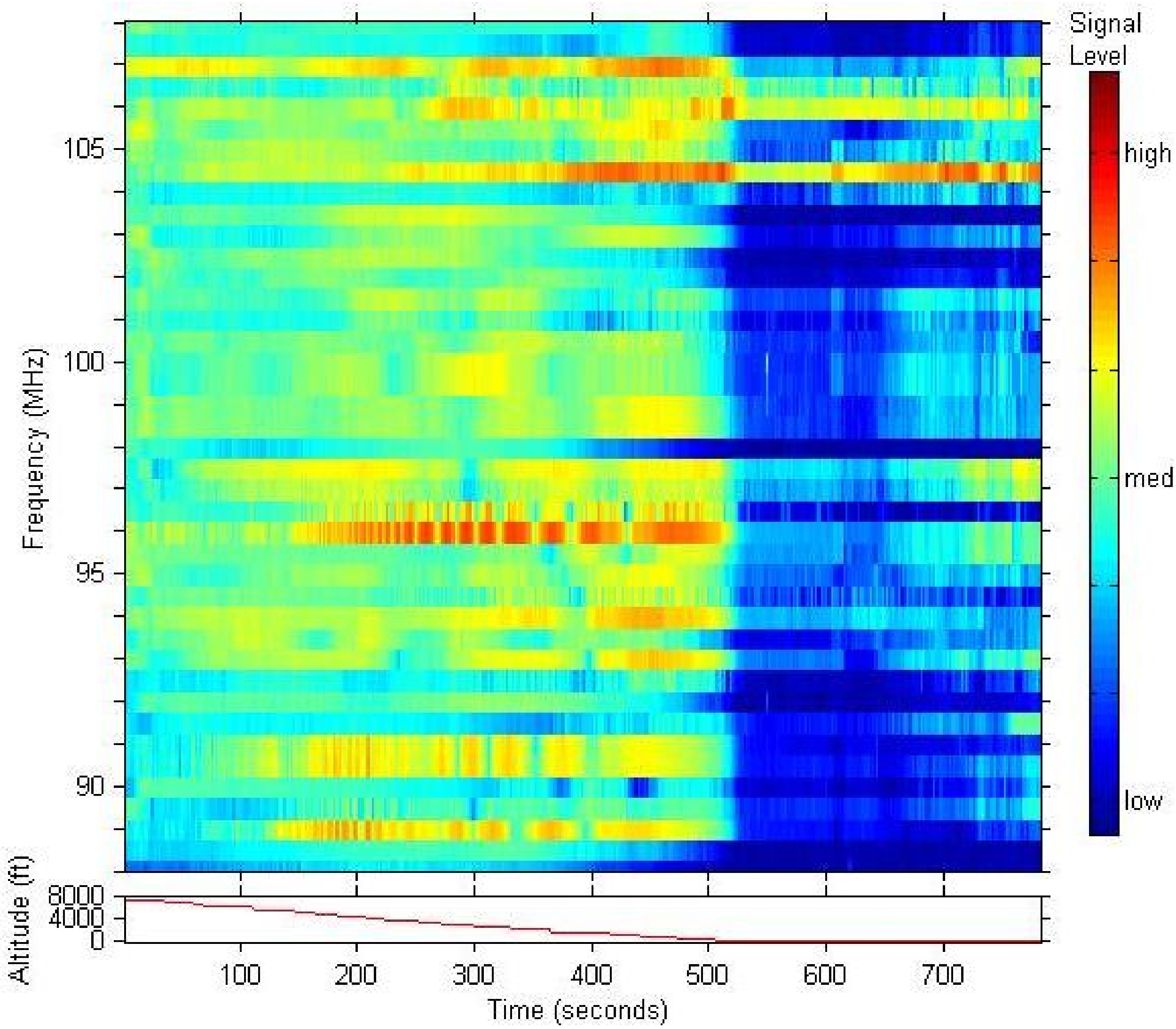


Figure 5-3: In-Flight Spectrum Environment for 88 to 108 MHz.

5.1.3 108 MHz to 138 MHz

The 108 MHz to 138 MHz RF band shown in Figure 5-4 is used exclusively for FAA licensed aeronautical radio. This entire RF band is critically important to aviation safety, and is expected to be free of interfering signals. Table 5-4 provides a summary of frequency allocations in the 108 to 138 MHz band. Table 5-5 contains a list of the local aeronautical frequencies in this band. Two distinctly different types of signals are used in this band: assigned communication channels that are used briefly and occasionally, and navigation beacons that are transmitting continuously.

The ILS localizer frequency (109.9 MHz) for this particular airfield is observed in Figure 5-4 to increase while approaching the runway, and then to decrease upon passing the ground transmitter during landing. For navigation signals transmitted from other locations (i.e., 112.0, 116.9) Figure 5-4 shows a continuous reduction in received signal levels as the altitude decreases. The very high (dark red) signal bursts in Figure 5-4 are from the ARMS aircraft's own VHF radio transmitter. Similar, but lower-level VHF radio communications can be seen at other times and at other frequencies. Table 5-5 provides a list of field evaluation frequencies that were measured and identified from Figure 5-4.

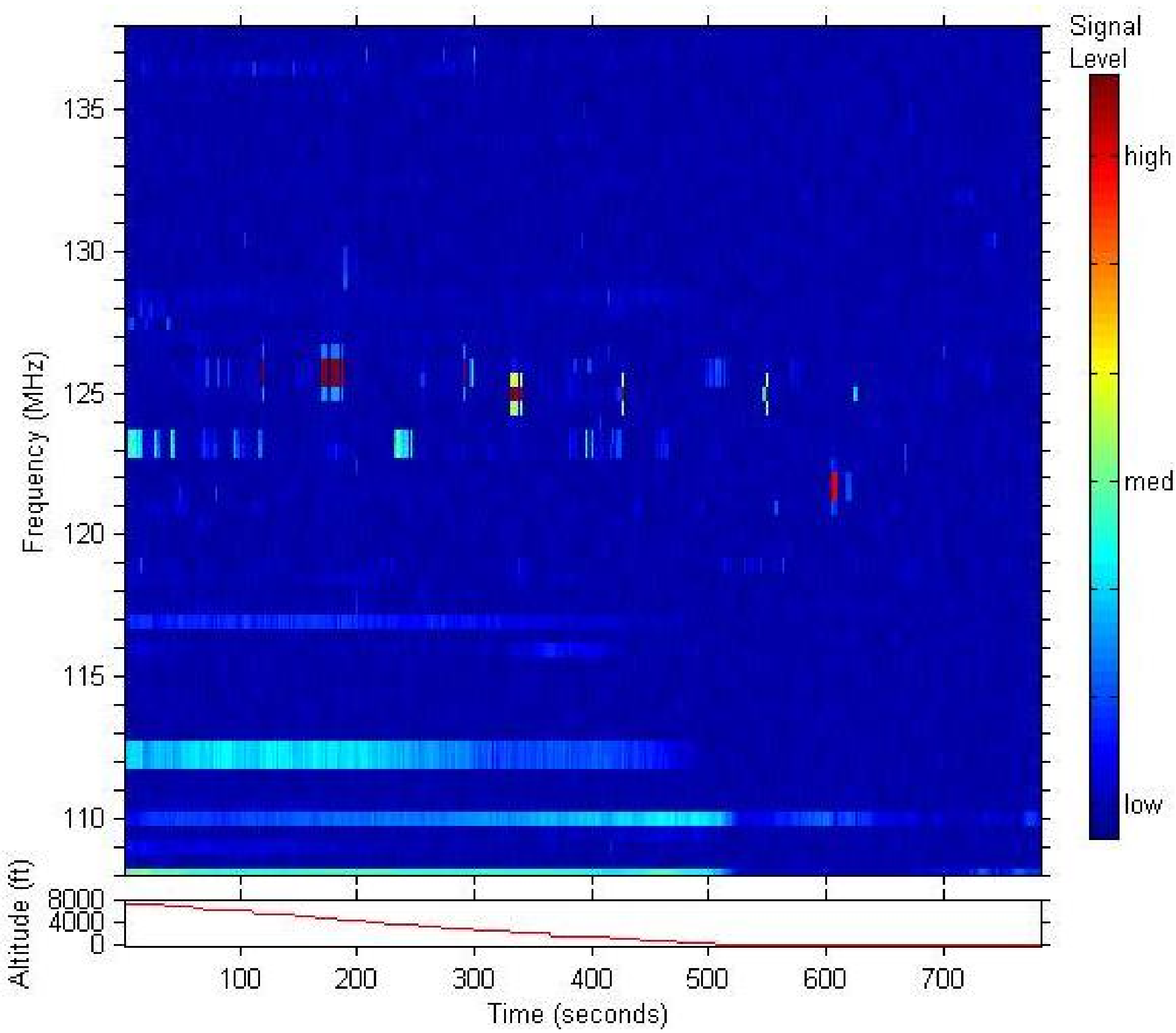


Figure 5-4: In-Flight Spectrum Environment for 108 to 138 MHz.

Table 5-4: Frequency Allocation Summary for 108 to 138 MHz

Frequency (MHz)	**Use**
108 – 117.975	Aeronautical radio Navigation (112 – 118 MHz: VOR, ILS LOC)
117.975 – 121.9375	Aeronautical Mobile. Air Traffic Controllers
121.9375 – 123.0875	Mobile units at airports. Unicom weather data, flight service communication
123.5875 – 138.8125	VHF Air Traffic Control

Table 5-5: Local Aeronautical Frequencies Observed in Test Data for 108 to 138 MHz

Frequency (MHz)	**Modulation Setting**	**Description of Audible Signal**
108.8	AM	VOR (nearby airfield)
109.1	AM	ILS signal (nearby airfield)
109.9	AM	Local Airfield ILS signal
112.0	AM	VOR (nearby airfield)
112.2	AM	VOR (nearby airfield)
116.9	AM	VOR (nearby airfield)
118.7	AM	VHF COM Tower (nearby airfield)
121.7	AM	VHF COM Ground Operations
123.375	AM	VHF COM NASA Operations
125.0	AM	VHF COM Tower
125.7	AM	Approach

5.1.4 138 MHz to 174 MHz

The 138 MHz to 174 MHz RF band shown in Figure 5-5 is used for numerous licensed radio services, including military, government, amateur, maritime, fire, police, business, etc. Table 5-6 provides a summary of frequency allocations for this RF band. Again, it is interesting to note which signals decline significantly with altitude (upon landing). The signal level change versus altitude may to be a good indication of the distance between landing site and location of signal transmission. While the aircraft antenna used for this ARMS flight is not optimized for this RF band, it is evident that meaningful data was acquired. Appendix A of this report provides insight about expected performance when using antennas outside their intended RF band. Table 5-7 shows that some of the signals identified during the ARMS RF survey were not measured during the field evaluation measurements, i.e., 139, 142, 143, 145 MHz. These signals were either physically not present at the time of the field measurements or undetectable using the handheld scanner.

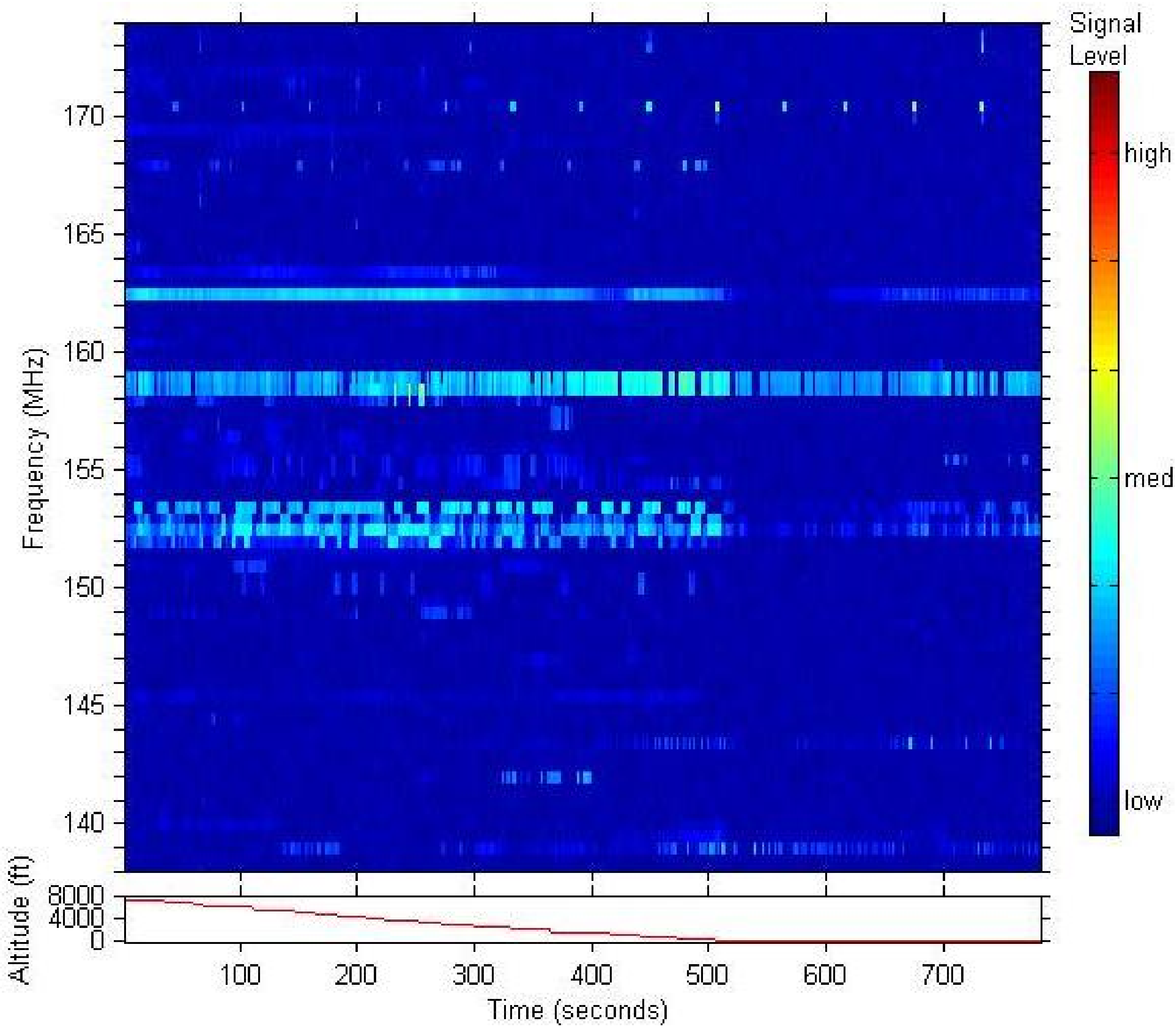


Figure 5-5: In-Flight Spectrum Environment for 138 to 174 MHz.

Table 5-6: Frequency Allocation Summary for 138 to 174 MHz

Frequency (MHz)	Use
138 – 144	Fixed Mobile. Government Band: air traffic control, security and alarms, depot maintenance, special investigations, fire and medical communications
144 – 146	Amateur Radio (ham radios). Worldwide band. (145.8 MHz: ham operating on Space Station)
146 – 148	Amateur radio (Americas, Greenland, and Asia-Pacific)
149.9 – 150.05	International allocated to Mobile Satellite Service for land operations only and to Radio Navigation Satellite Service
150.05 – 150.8	Fixed. Mobile. Army, Air Force, and Navy. Non-government Emergency Medical Radio Service.
150.8 – 152.855	Fixed. Land Mobile. Public Safety pool frequencies (highway maintenance and forestry). Industrial/Business pool for general commercial use. **one of the bands containing low power "color dot" frequencies – inexpensive, OTS radios pretuned to one of several frequencies. Choosing dots of the same color ensure units on same freq and able to intercommunicate. MURS (multi-use radio service) freqs in Citizen Band Radio Services – used to transmit data and image communications as well as voice (151.820, 151.880, 151.940)

Frequency (MHz)	Use
152.855 – 154	Land Mobile. Fire protection and other public safety applications. Industrial/Business uses – power utility communications and remote pick-up systems in radio and TV broadcasting.
157.45 – 161.575	Public Mobile. Private Land Mobile, Maritime. Industrial/Business and Public Safety Private Mobile Radio Services frequencies. Conventional Rural Radiotelephone Stations. Key VHF band for railroad communications. Power utilities, police radio, highway maintenance, forestry, BAS (Broadcast Auxiliary Services)
161.775 – 162.0125	VHF Maritime. Ship telephone service.
162.0125 – 173.2	Fixed. Mobile. Federal VHF band [162.0125 – 173.2] Federal law enforcement, transportation, emergency response, utility operation, weather broadcast. FBI, DEA, Customs Service, Bureau of Alcohol, Tobacco and Firearms use for agent-to-agent communication. (173.075 – LoJack (Stolen Vehicle Recovery Systems)) (162.400, 162.425, 162.450, 162.475, 162.500, 162.525, 162.550 – National Weather Service)

Table 5-7: Field Evaluation of Signals Using a Handheld Scanner for 138 to 174 MHz

Frequency (MHz)	Modulation Setting	Date	Description of Audible Signal
152.0 to 154.0	AM & FM	7/17/06 & 10/10/06	Tones, noise, “modem-like” sounds
158.0	AM	7/17/06	Continuous tone with “modem-like” sounds
158.520	FM	10/10/06	Occasional break-squelch. No tones or voices
159.135	FM	10/10/06	Voice Communication: Police Radio conversation
162.550	FM	7/17/06	National Weather Service audio
168.0	FM	7/17/06	“Modem-like” sounds
170.505	WFM	10/10/06	Strong signal, no audio, 2 sec duration, repeat every 60 seconds

5.1.5 174 MHz to 216 MHz

The 174 MHz to 216 MHz RF band shown in Figure 5-6 is used almost exclusively for television broadcast, channels 7 to 13. While airborne, it is apparent that signals from all seven television channels are received. Even so, there is still a noticeable percentage of “blue” in the plot. This is because all of the television channels are National Television System Committee (NTSC) channels, rather than digital television (DTV) channels in the local area. (Section 5.1.8 includes data for DTV channels for comparison.) As noted in previous RF bands, there is a reduction in some received signal levels as the altitude decreases and a significant decrease at ground level (after 500 seconds). Also as noted in previous sections, receive signal level reductions may occur in each signal (versus time) due to line-of-site shading by the airplane wings and fuselage or terrain reflections.

Because this entire band is allocated exclusively to television, the handheld scanner was not used to investigate received signals. The audio frequencies for each TV channel are provided in Table 5-8 for reference.

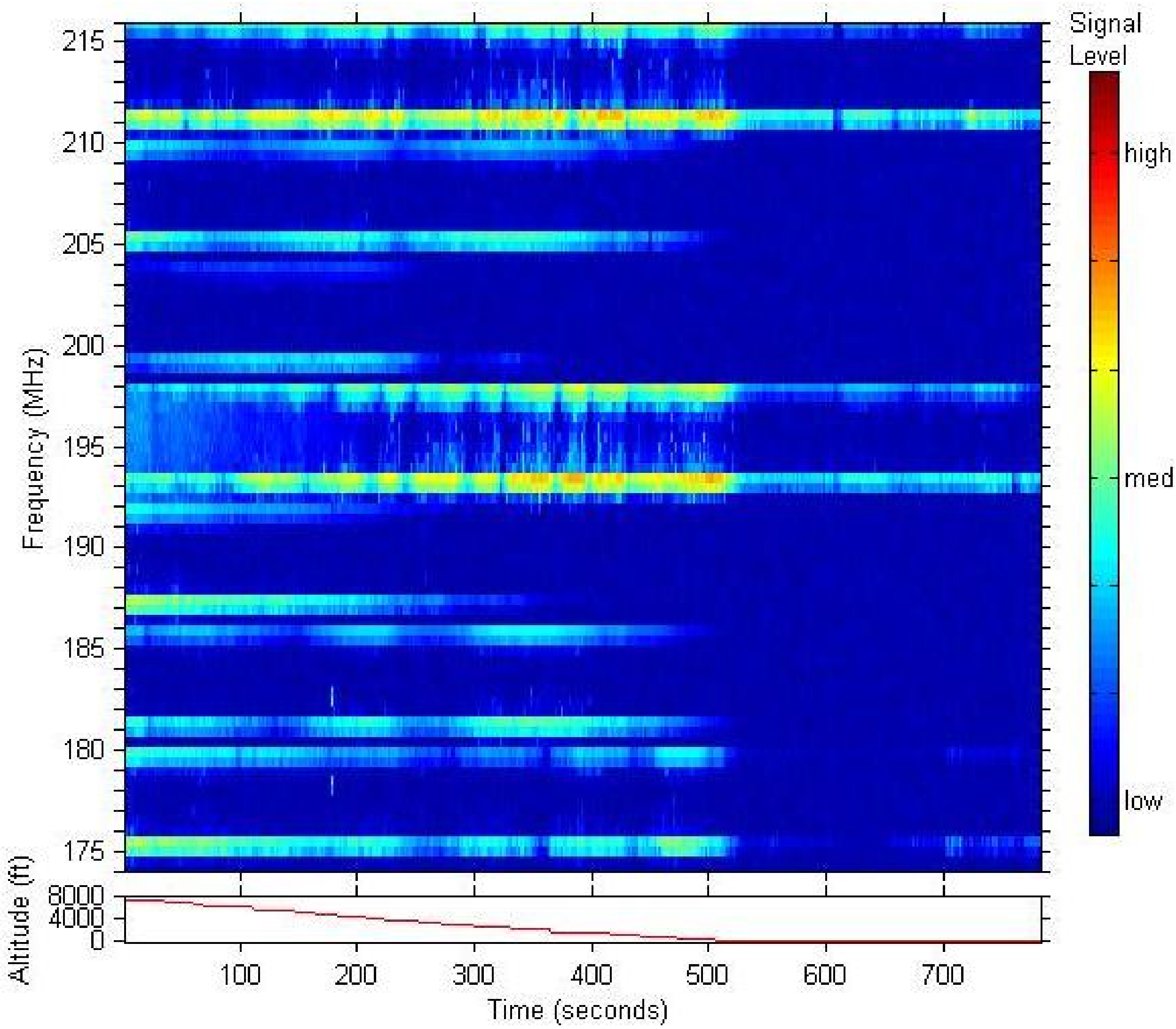


Figure 5-6: In-Flight Spectrum Environment for 174 to 216 MHz.

Table 5-8: Frequency Allocation Summary for 174 to 216 MHz

Frequency (MHz)	**Use**
174 – 180 (audio on 179.75)	TV Channel 7
180 – 186 (audio on 185.75)	TV Channel 8
186 – 192 (audio on 191.75)	TV Channel 9
192 – 198 (audio on 197.75)	TV Channel 10
198 – 204 (audio on 203.75)	TV Channel 11
204 – 210 (audio on 209.75)	TV Channel 12
210 – 216 (audio on 215.75)	TV Channel 13

5.1.6 216 MHz to 400 MHz

The 216 MHz to 400 MHz RF band shown in Figure 5-7 is used mostly for military and federal government, but is also home for licensed radio services, including amateur, maritime, business, etc. Table 5-9 provides a summary of frequency allocations for this RF band. The aircraft antenna used for this ARMS flight is optimized for the 328 MHz to 336 MHz portion of this RF band. Only two signals are discernable in the entire RF survey data image shown in Figure 5-7. Section 5.2 and Appendix A of this report provides insight about expected performance when using antennas outside their intended RF band.

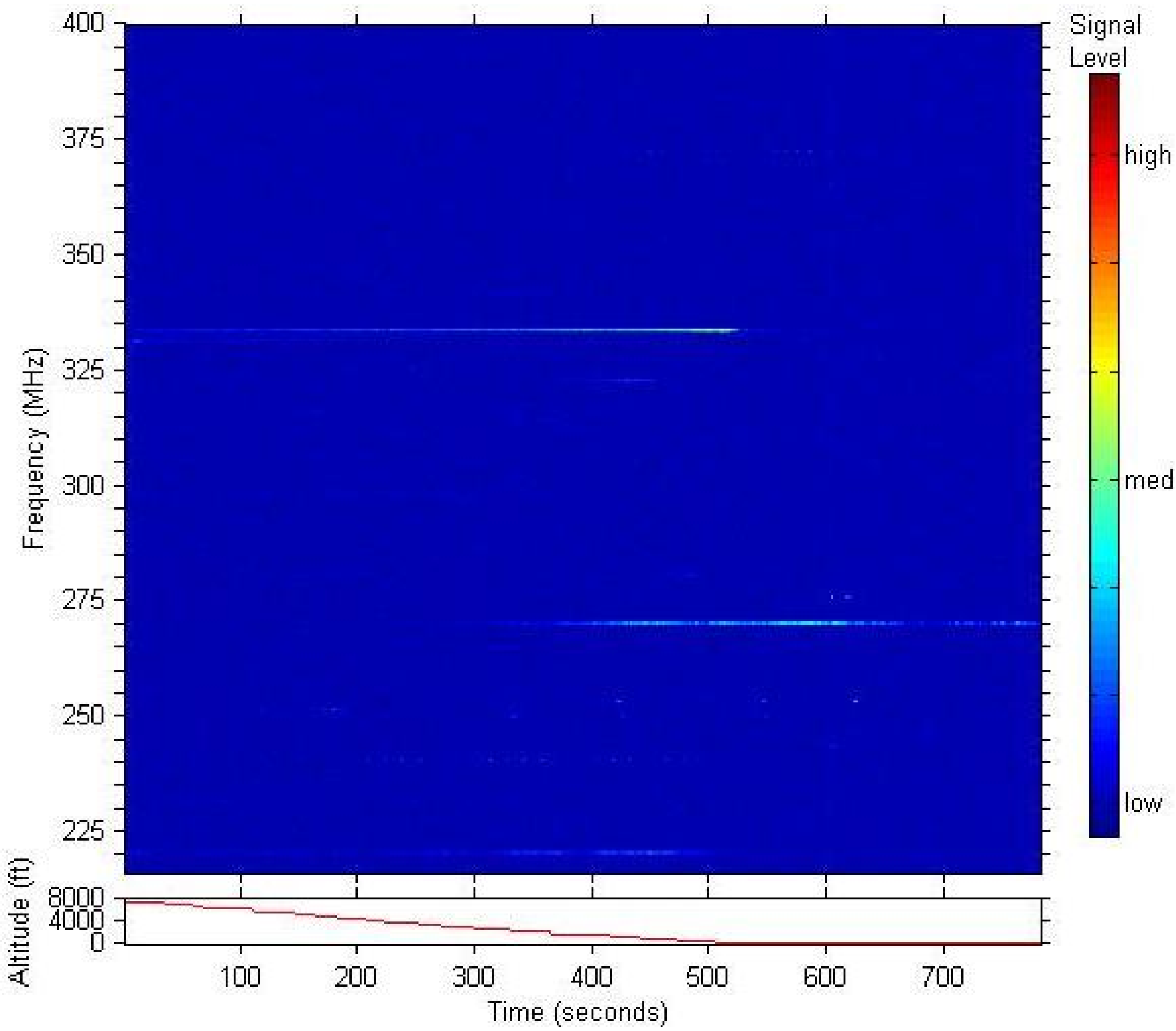


Figure 5-7: In-Flight Spectrum Environment for 216 to 400 MHz.

Table 5-9: Frequency Allocation Summary for 216 to 400 MHz

Frequency (MHz)	Use
216 – 225	Space Radar, transportation, telemetry, amateur, personal radio services
225 – 240	Military Spectrum "most critical spectrum resource of military tactical forces"
243.0	Emergency locator transmitters
267 – 322	Military Restricted band, Fixed. Mobile.
322– 328.6	Military Restricted band, Radio Astronomy
328.6 – 335.4	Aeronautical Radio Navigation. Devoted to ILS GS

Table 5-10 summarizes the findings of the field evaluation performed with a handheld scanner. It is interesting to note that the local airport Automatic Terminal Information System (ATIS, 270.1 MHz) increases in amplitude as approached by the airplane during landing. This is because the transmitter is typically located at the airport. It is also interesting and expected that the ILS GS signal (333.5 MHz) increases, but suddenly declines as the airplane passes by the ground beacon antenna.

Table 5-10: Field Evaluation of Signals Using a Handheld Scanner for 216 to 400 MHz

Frequency (MHz)	Modulation Setting	Date	Description of Audible Signal
270.100	AM	10/10/06	Local airport Automatic Terminal Information System (ATIS)
333.8	CW	10/10/06	Local airfield ILS GS signal

5.1.7 400 MHz to 470 MHz

The 400 MHz to 470 MHz RF band shown in Figure 5-8 is used for many licensed radio services, including general aviation, citizen's band, amateur, radio astronomy, fire, police, business, etc. Table 5-11 provides a summary of frequency allocations for this RF band. While the aircraft antenna used for this ARMS flight is not optimized for this RF band, it is evident that meaningful data was acquired. Section 5.2 and Appendix A of this report provides insight about expected performance when using antennas outside their intended RF band. Table 5-12 summarizes the findings of the field evaluation performed with a handheld scanner.

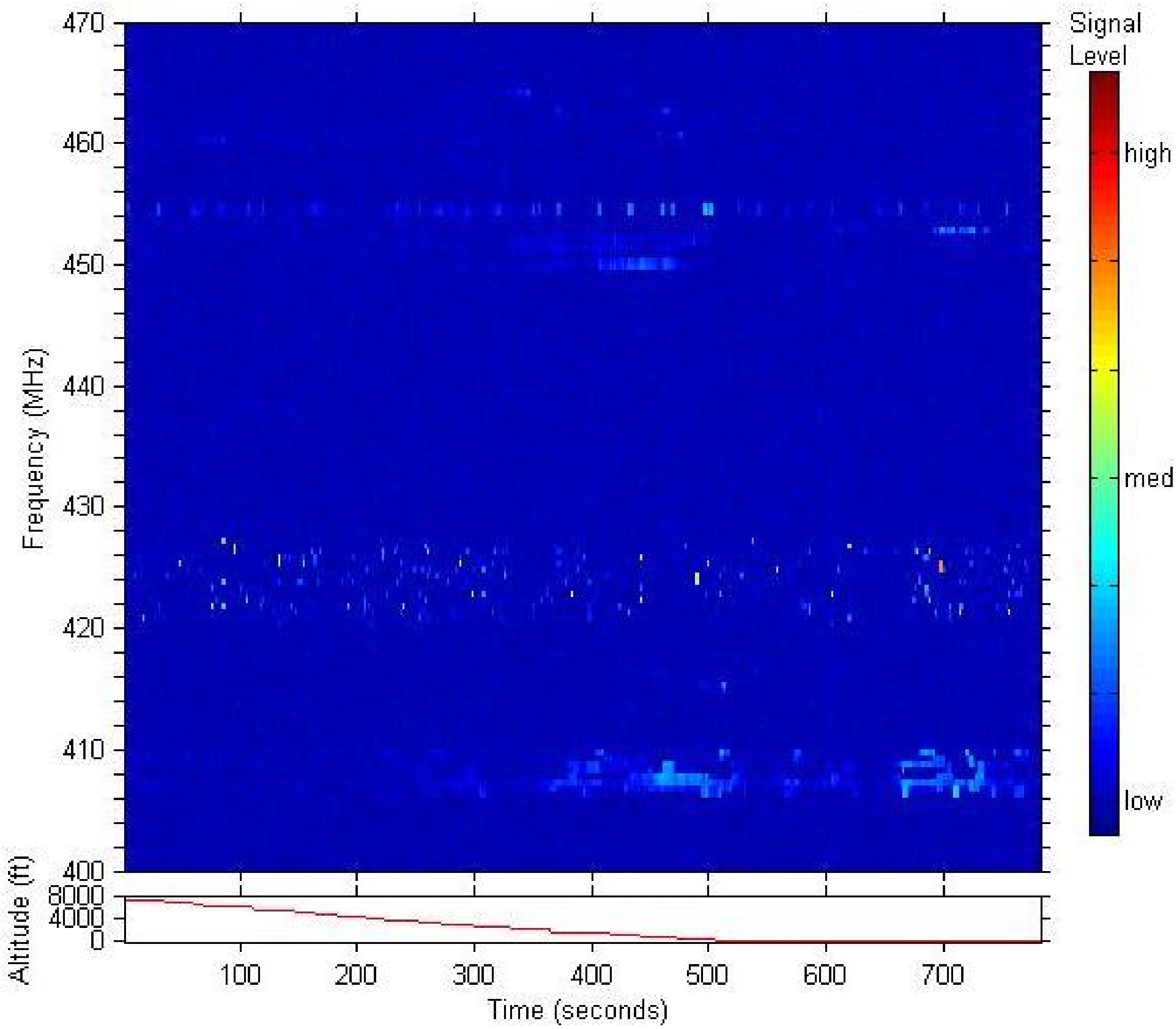


Figure 5-8: In-Flight Spectrum Environment for 400 to 470 MHz.

Table 5-11: Frequency Allocation Summary for 400 to 470 MHz

Frequency (MHz)	Use
406	Search and Rescue Emergency Transmitter Beacons (i.e. SARSAT/COSPAS, Distress Alerting Satellite System transponders) on GPS Block III.
406.1 – 410	Fixed. Mobile. Radio Astronomy (exclusive non-government user). Main general-purpose federal UHF land mobile bands. Communications for law enforcement. Air Force radar, paging, range control, fire protection, transportation, and security.
420 – 430	Amateur TV
421 – 430	Private Mobile. Radio Services
450 – 451	Base stations.
451 – 454	Base station segment, which has channels for mobile units at 456 – 460 MHz. Marks the start of the principal UHF Private Mobile Radio Services allocations.
454 – 455	General Aviation Air-Ground Radiotelephone Service
455 – 456	Mobile units by TV and radio stations in the Broadcast Auxiliary Service.
456 – 460	Mobile radio services, General Aviation Air-ground Radiotelephone Service

Frequency (MHz)	Use
460 – 462.5375	Base stations, UHF Private Mobile Radio Services allocations spectrum and their Industrial/Business and Public Safety frequency pools. 460-461 MHz frequencies are available for experimental use by students and schools.
462.5375 – 462.7375	General Mobile Radio Service (GMRS) and Family Radio Service (FRS) 462.525-467.475MHz frequencies are available for experimental use by students and schools.
462.7375 – 467.5375	Private Carrier paging Systems. Public Safety frequency pool. Vessel Traffic Services. Police and fire channel.

Table 5-12: Field Evaluation of Signals Using a Handheld Scanner for 400 to 470 MHz

Frequency (MHz)	Modulation Setting	Date	Description of Audible Signal
403 to 410	AM, FM, CW, WFM	10/10/06	Tones, hums, buzzes. Intermittent, but strong RF level
420 to 430	AM	10/10/06	Tone ~1kHz
425.325 to 425.900	WFM	10/10/06	Bursts of white noise 1 burst-per-second. Some intermittent tones and "modem-like" bursts.
450.400	WFM	10/10/06	TV Audio, unidentified source
451.225	FM, WFM	10/10/06	Voice. Business Radio?
453.525	WFM	10/10/06	Voices, tones and "modem-like" sounds
454	WFM	7/17/06	"Modem-like" sounds
454.5	WFM	7/17/06	Tones and "Modem-like" sounds
458.2	WFM	10/10/06	Tones and "modem-like" sounds

5.1.8 470 MHz to 824 MHz

The 470 MHz to 824 MHz RF band shown in Figure 5-9 is used mostly for television broadcast, UHF-band, channels 14 to 67. Some of the channels are re-allocated to wireless services, medical telemetry, police, fire, etc. It is interesting to note which signals decline significantly with altitude (upon landing). Table 5-13 provides a summary of frequency allocations in the 470 to 824 MHz band. Also noted in previous sections of this report, pattern nulls can be observed in each signal (versus time) due to line-of-site shading by the airplane wings and fuselage. No field evaluations were performed in this band as the signals are known and can be identified in the data image.

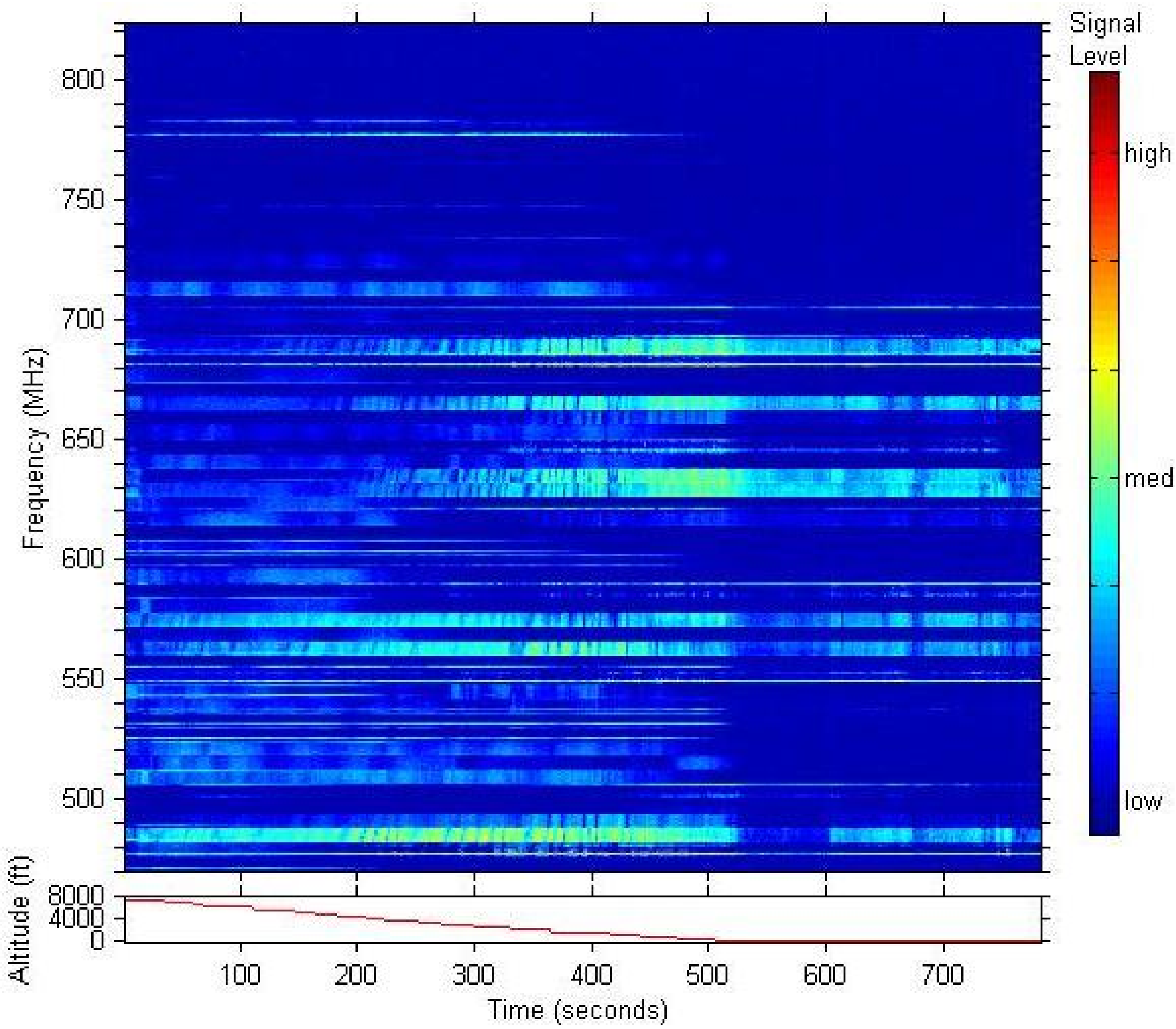


Figure 5-9: In-Flight Spectrum Environment for 470 to 824 MHz.

Table 5-13: Frequency Allocation Summary for 470 – 824 MHz

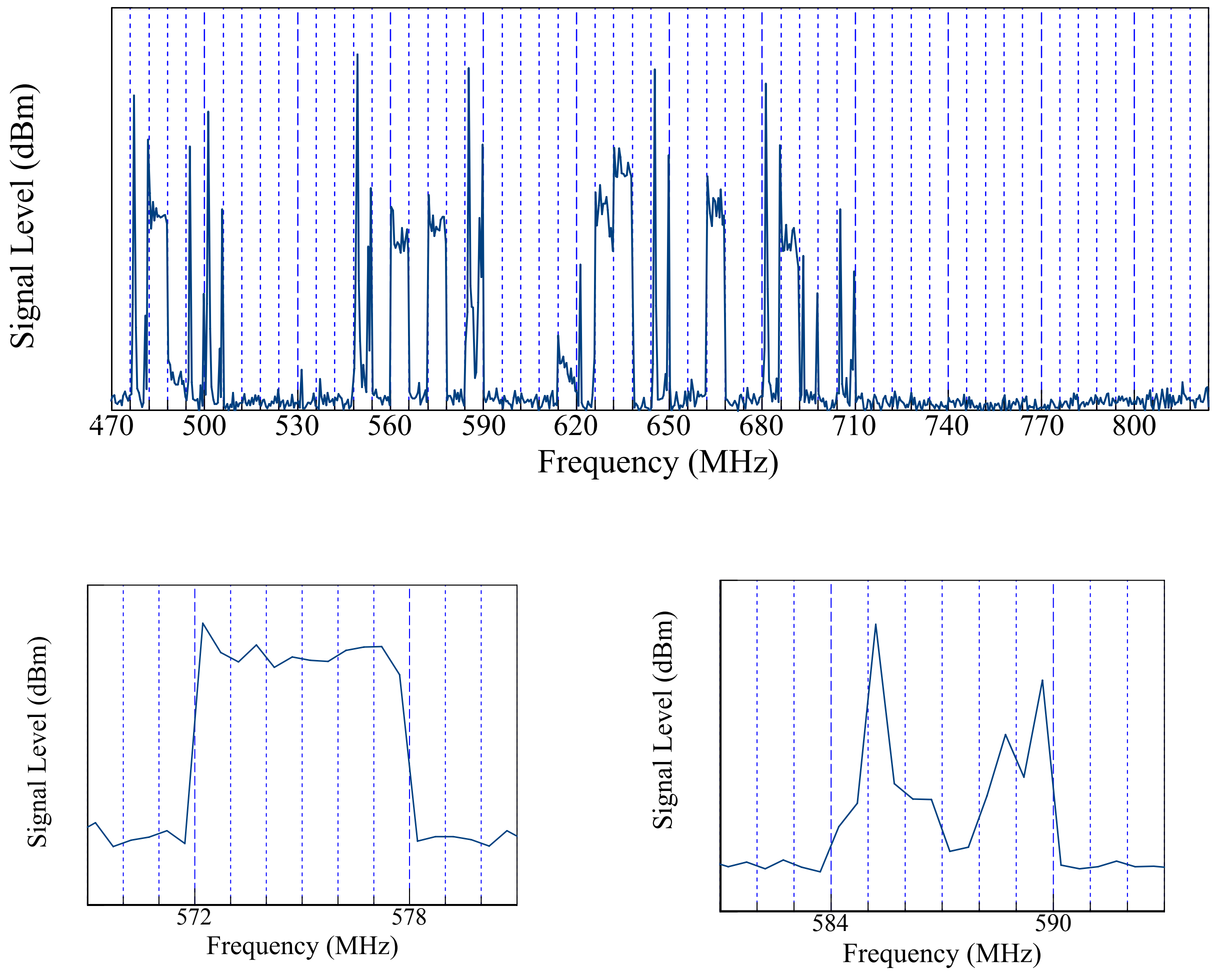
Frequency (MHz)	Use
470 – 512	UHF television channels 14 – 20.
512 – 608	UHF television channels 21 – 36.
608 – 614	TV channel 37. Radio astronomy continuum observations. Wireless Medical Telemetry Service.
614 – 698	UHF television channels 38 – 51.
698 – 746	UHF television channels 52 – 59.
746 – 764	UHF television channels 60 – 62. Wireless Communications Services.
764 – 776	UHF television channels 63 – 64. Police, fire, and emergency medical radio.
776 – 794	UHF television channels 65 – 67.

Table 5-14 shows the television channels that can be identified in Figure 5-9. The DTV Channels are highlighted in blue. Note that DTV channels occupy the same bandwidth (6 MHz) as NTSC channels, but are located at different frequencies. Probably the most interesting characteristic of the RF survey data image (Figure 5-9) is the notable difference between spectrum usages of NTSC versus DTV television channels. To better illustrate the differences, a single sample of data is shown in Figure 5-10. The DTV signal "fills-in" the channel spectrum more fully than the NTSC signal, which intuitively makes sense because it contains more information.

Table 5-14: Frequency Allocation Summary for 470 – 824 MHz

Channel Designation	Frequency	Modulation	Station ID
15	476-482	NTSC	Hampton/Norfolk CH 15
16	482-488	DTV	Hampton/Norfolk CH 15
19	500-506	DTV	Portsmouth CH 27
26	542-548	DTV	Richmond CH 35
27	548-554	NTSC	Portsmouth CH 27
29	560-566	DTV	VA Beach CH 43
31	572-578	DTV	Portsmouth CH 10
33	584-590	NTSC	Norfolk CH 33
35	596-602	NTSC	Richmond CH 35
38	614-620	DTV	Norfolk CH 33
41	632-638	DTV	Hampton CH 13
43	644-650	NTSC	VA Beach CH 43
44	650-656	DTV	Richmond CH 57
46	662-668	DTV	Norfolk CH 49
49	680-686	NTSC	Norfolk CH 49
57	728-734	NTSC	Richmond CH 57
58	734-740	DTV	Norfolk CH 3
65	776-782	NTSC	Ashland CH 65

(a)



(b) (c)

Figure 5-10: (a) Single ARMS spectrum sample from 470 to 824 MHz (obtained after landing). (b) Close-up of TV Channel 31 (DTV Channel 10) from 572 to 578 MHz. (c) Close-up of TV Channel 33 (NTSC) from 584 to 590 MHz.

5.1.9 824 MHz to 901 MHz

The 824 MHz to 901 MHz RF band shown in Figure 5-11 is used mostly for cellular telephone handsets and base stations, but is also important for public safety radio services, private land mobile, and airplane telephone service. Table 5.15 provides a summary of frequency allocations for this RF band. While the aircraft antenna used for this ARMS flight is not optimized for this RF band, it is evident that meaningful data was acquired. Section 5.2 and Appendix A of this report provides insight about expected performance when using antennas outside their intended RF band. Table 5-16 summarizes the findings of the field evaluation performed with a handheld scanner.

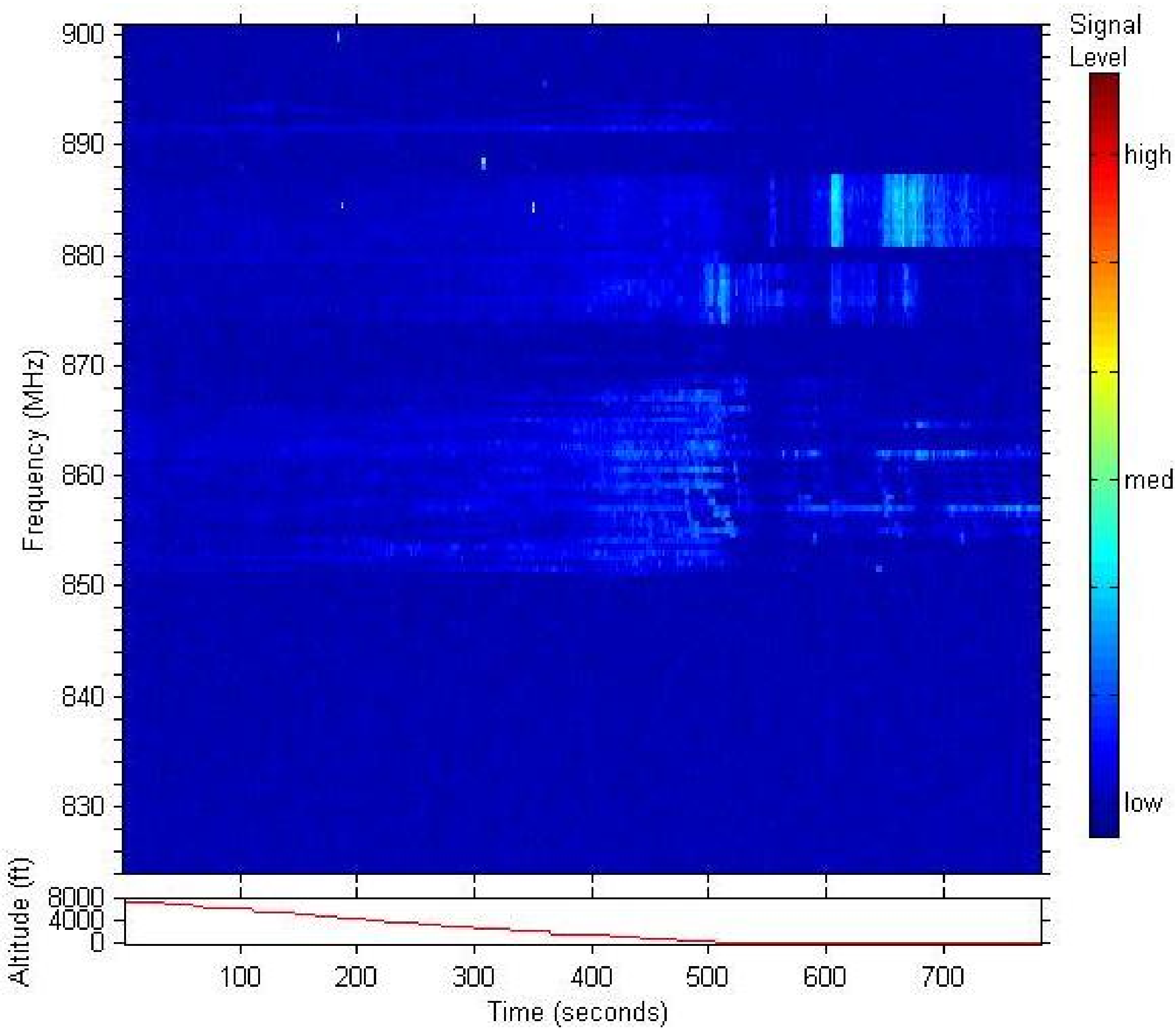


Figure 5-11: In-Flight Spectrum Environment for 824 to 901 MHz.

Table 5-15: Frequency Allocation Summary for 824 to 901 MHz

Frequency (MHz)	Use
824 – 849	Cellular Radiotelephone Service.
849 – 851	Uplink band for Commercial Aviation Air-Ground Systems.
851 – 866	Base-to-mobile frequencies for conventional and trunked private land Mobile Radio Services.
866 – 869	Base-to-mobile frequencies for public safety licensees under the FCC national public safety radio plan.
869 – 894	Base stations in the Cellular Radiotelephone Service transmit to mobile units.
894 – 896	Downlink band for Commercial Aviation Air-Ground Systems.
896 – 901	Mobile-to-base frequencies for the 900 MHz version of Specialized Mobile Radio (SMR).

Table 5-16: Field Evaluation of Signals Using a Handheld Scanner for 824 to 901 MHz

Frequency (MHz)	Modulation Setting	Date	Description of Audible Signal
853 – 856	FM	10/10/06	Tones, noise, hums
859.912	FM	10/10/06	Voice, Business Radio
860.212 to 866.9	FM	10/10/06	Voice, Police Radio channels
874 to 879	FM	10/10/06	Tones, noise, hums. High signal strength
880.0 to 880.5	FM	10/10/06	~2kHz tones
881 to 887	FM	10/10/06	Broadband noise
889.162	FM	10/10/06	Cellular Phone Call
893.487	FM	10/10/06	Cellular Phone Call

5.1.10 901 MHz to 1000 MHz

The 901 MHz to 1000 MHz RF band shown in Figure 5-12 is used for unlicensed industrial-scientific-medical (ISM) devices, aeronautical distance measuring equipment (DME), television auxiliary broadcast service, government radio communication links, and other assorted communication services. Table 5.17 provides a summary of frequency allocations for this RF band. While the aircraft antenna used for this ARMS flight is not optimized for this RF band, it is evident that meaningful data was acquired. Section 5.2 and Appendix A of this report provides insight about expected performance when using antennas outside their intended RF band. Table 5-18 summarizes the findings of the field evaluation performed with a handheld scanner.

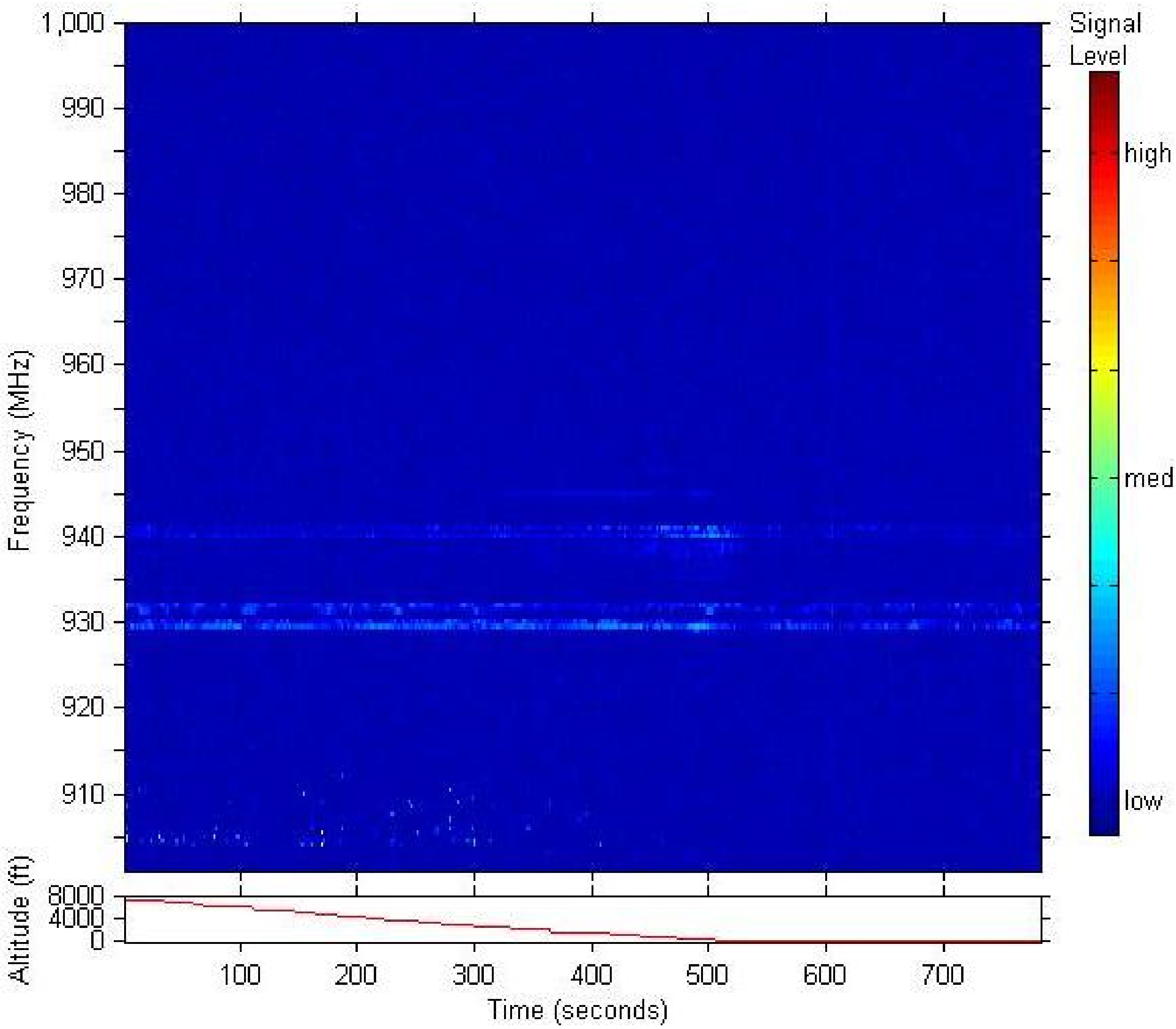


Figure 5-12: In-Flight Spectrum Environment for 901 to 1000 MHz.

Table 5-17: Frequency Allocation Summary for 901 to 1000 MHz

Frequency (MHz)	Use
902 – 928	Industrial-scientific-medical (ISM, or "kitchen sink" band). Cordless phones, listening devices, wireless local area networks, military radars, and commercial Location and Monitoring Service systems. Amateur Radio band.
930 – 931	Narrowband Personal Communications Services band.
931 – 932	Internal paging within organizations and for Commercial Mobile Radio Service (CMRS) paging in the Private and Public Mobile Services.
940 – 941	Narrowband Personal Communications Service
941 – 944	Shared by Fixed Services, including Multiple Address Systems (MAS).
944– 960	Radio & TV station BAS, STL, ICR, MAS
960– 1000	Part of the 960 to 1215 MHz aeronautical radionavigation band, including DME, GPS L5 and aircraft transponders.

Table 5-18: Field Evaluation of Signals Using a Handheld Scanner for 901 to 1000 MHz

Frequency (MHz)	Modulation Setting	Date	Description of Audible Signal
929.20 to 930.25	FM	10/10/06	~3kHz tones, static
937.5 to 941	WFM	10/10/06	Tones, beeps, "modem-like" sounds, "motorboating" sounds

5.2 Data Calibration

The spectrum environment data graphs in Section 5.1 show un-calibrated data. This section explores how calibrations may be applied for particular scenarios. Electric field intensities and/or available power levels in the surveyed airspace are dependent upon the type of aircraft antenna used, its orientation relative to each environmental transmitter, separation distance between each environmental transmitter and the ARMS antenna, the power output of each environmental transmitter, and the environmental transmitter antenna gain in the direction of the ARMS airplane. To determine the power measured at the ARMS spectrum analyzer input connector, the transmission equation is:

$P_{Rcv} = [P_{Source} + G_{Source}] - L_{Prop} + [G_{AC\_Ant} - L_{Cbl}]$ (dB), [Eq. 5-1]

Where:

$P_{Rcv}(t,f,n,lat_{rcv},lon_{rcv},alt_{rcv})$ = Power received at the aircraft radio connector for each frequency (f), each environmental transmitter (n), and aircraft position (lat, lon, alt), at a given time (t).

P_{Source} $(t,f,n,lat_{source},lon_{source},alt_{source})$ = Power transmitted from each environmental transmitter (n) for each frequency (f), and source location (lat,lon,alt), at a given time (t).

$G_{Source}(f, \theta, \varphi)$ = Environmental Source Antenna Gain (relative to isotropic, in direction of ARMS airplane).

$L_{Prop}(f,n, lat_{rcv}, lon_{rcv}, alt_{rcv}, lat_{source}, lon_{source}, alt_{source})$ = |Propagation loss| between each signal source (n) and aircraft antenna, for each frequency (f).

$G_{AC\_Ant}(f, \theta, \varphi)$ = Aircraft Antenna Gain (relative to isotropic, in direction of signal source).

$L_{Cbl}(f)$ = |Onboard Cable loss|.

All variables are in dB units. Note that P_{Rcv}, P_{Source} and L_{Prop} are also functions of position (latitude, longitude and altitude) of the ARMS aircraft when the measurement occurred. A graphical diagram of this equation is shown in Figure 5-13. The ARMS also records the GPS time along with latitude and longitude for each P_{Rcv} data point. The primary purpose of the ARMS was to directly measure ILS signal coverage around airports (i.e. P_{Rcv}, with some prior knowledge of P_{Source} and G_{Source}). Other ARMS' applications may include detecting and characterizing power output, antenna patterns, locations and operating frequencies of ground sources.

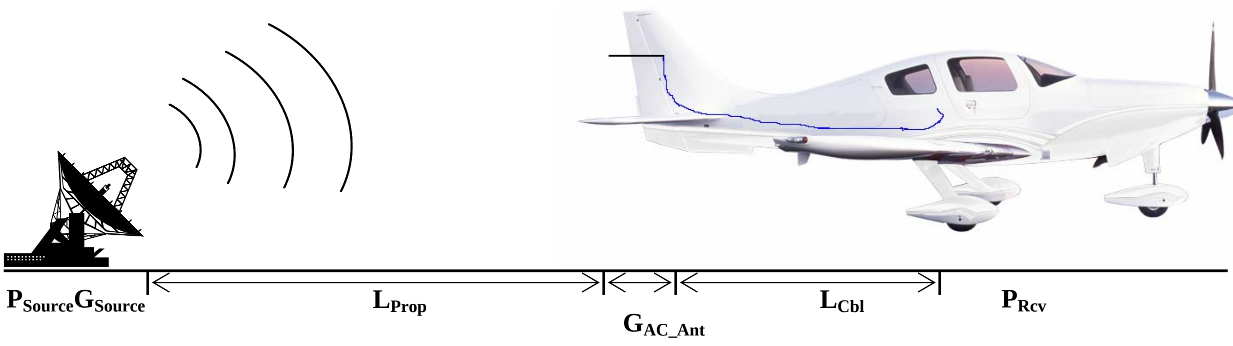


Figure 5-13: Diagram of transmission equation as applied to ARMS.

Propagation loss is a standard quantity and is given as:

$L_{Prop}(f,n,Distance) = 20Log[c/(4\pi f \cdot Distance)]$ (dB), [Eq. 5-2]

Where:

c = Velocity of signal propagation. Usually assumed equal to light in free space, c= 3 x 10^8 meters/sec.

f = Radio frequency of operation (Hz).

Distance (n, lat_{rcv}, lon_{rcv}, alt_{rcv}, lat_{source}, lon_{source}, alt_{source}) = Separation distance between transmitter (n) antenna and ARMS aircraft antenna (Meters).

Distance is automatically calculated from the ARMS aircraft latitude, longitude and altitude (and time), and recorded for each measurement, when the transmitter location is known. (See Section 2.)

It is important to address efficiency (reflection and resistive loss) as part of G_{AC_Ant} if measuring outside its design frequency band. G_{AC_Ant} consists of three components:

$G_{AC\_Ant} = D_{AC\_Ant} - L_{Refl} - L_{Res}$ (dB), [Eq. 5-3]

Where:

$D_{AC\_Ant}(f)$ = Directivity of the Aircraft Antenna,

$L_{Refl}(f)$ = Reflection Loss of the Aircraft Antenna,

$L_{Res}(f)$ = Resistive Loss of the Aircraft Antenna.

Reflection loss $L_{Refl}(f)$ and resistive loss $L_{Res}(f)$ may be significant for an antenna operating outside it's design frequency band. Also, when an antenna is used at higher-than-intended frequencies, nulls occur in the directivity pattern. These factors can easily equate to many dB, and are difficult to calculate and measure. It is therefore useful to address aircraft antenna "in-band" and "out-of-band" ARMS measurements differently. The next section describes the aircraft antenna in-band calibration scenario for an ILS IAP. Aircraft antenna out-of-band calibration was not required for experiment data shown in this report, however some general guidelines for such a calibration are provided in Appendix A.

5.3 ILS Localizer and Glideslope Measurement Results

The ARMS measured the LOC and GS RF signal levels in an ILS approach path during the airport RF measurement survey. The ARMS included a Comant CI 159C dual-band V-Dipole antenna that is specifically designed for LOC and GS, and has a VSWR of 3:1 or less in both RF bands.

This is the simplest calibration scenario because the aircraft antenna design and installation is optimized to minimize reflection and resistive loss for the frequencies-of-interest, and to maximize directivity toward the intended transmitter during an ILS approach.

For the ARMS installation, a spectrum analyzer replaced one of the Apollo SL-30 navigation and communication radios as shown in Figure 5-14 and Figure 2-8. The cable loss difference between the spectrum analyzer cable and the SL-30 #2 cable is negligible (less than 1dB) in the ILS RF bands. So, for the purpose of comparing available ILS signal levels at the spectrum analyzer versus the aircraft radio receiver, no calibration factors are required.

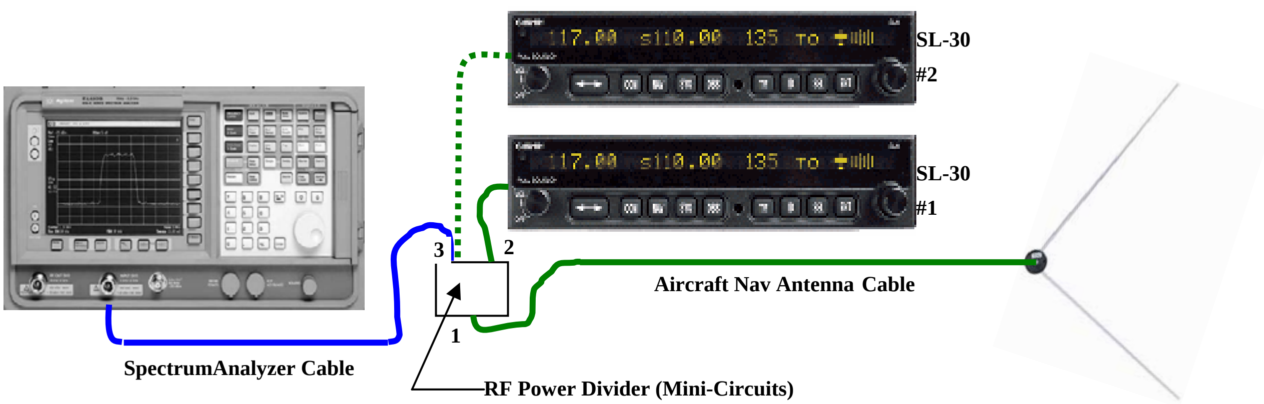


Figure 5-14: RF Pathway between Spectrum Analyzer and Comant CI 159C dual-band V-Dipole antenna.

To evaluate the signal coverage volume of the airport ILS services [$P_{Source} + G_{Source} - L_{Prop}$], it is necessary to consider the Mini-Circuits zfsc-2-1b RF power divider loss (about 3dB), the aircraft antenna cables (about 3dB) and the Comant CI 159C antenna gain ($G_{AC_Ant} = 0$dB). Rearranging Equation 5-1, we can obtain the ILS signal power available at a particular aircraft location:

$[P_{Source} + G_{Source}] - L_{Prop} = P_{Rcv} - [GA_{C\_Ant} + L_{Cbl}]$ (dB), [Eq. 5-4]

Where:

L_{Cbl} (f) = Power Divider Loss + Aircraft Antenna Cable Loss

(Note that L_{Cbl} (f) = Receive path loss (or $-G_{Rcv\_path[dBm]}$) used in Section 2.3.)

The specific frequencies for ILS localizer and ILS glideslope from the approach and landing data sample described in Section 5.1 are plotted in Figure 5-15. The signal levels are shown to gradually increase while approaching the runway. As the aircraft passed the localizer and glideslope antenna arrays during final descent, the signal levels fall dramatically. Once on the ground, data continued to be collected for about 250 seconds as the aircraft taxied down the runway, exited the runway, and proceeded to a nearby hangar. The Distance-to-Runway is calculated using

equations in Section 2.3.2 where it is defined as the distance measured between the runway reference coordinates (end point) and the aircraft's location. The Distance-to-Runway and the Altitude data (Figure 5-15) are closely correlated due to the constant glideslope. It is interesting to note the apparent "jumps" in the Distance-to-Runway and Altitude data. This may be caused by updates in the GPS position. The GPS receiver provides periodic updates in the GPS position via the RS-232 data bus, which is monitored by the ARMS. Such discontinuities were not observed on the cockpit displays during flights. Further investigation of the data is planned as time permits.

L_{Prop} can be calculated using Equation 5-2. The ILS ground beacon EIRP [P_{Source} + G_{Source}] can then be determined from data shown in Figure 5-15.

Figure 5-15: In-Flight localizer and glideslope levels on ILS approach.

The ARMS can be connected to any other aircraft-mounted antenna. In fact, other NASA aircraft have been modified to provide an interchangeable, aluminum antenna-mount platform. A simple modification on the Lancair Columbia 300 can allow the use of numerous in-band antenna options for the ARMS.

6 Summary and Conclusions

The ARMS provides an automated data acquisition capability that can capture and record maximum RF signal levels together with complete spectrum analyzer measurement trace data. Each measurement is coordinated with time-stamped GPS latitude and longitude. The ARMS was utilized as a resource for environmental electromagnetic hazards research under the Integrated Vehicle Health Management (IVHM) element of NASA's Aviation Safety Program. The system was successfully installed on a general aviation aircraft, and used to conduct measurements of aeronautical radio frequencies during flight surveys near several airports. A sample of the RF environment data (300 MHz to 1000 MHz) that was acquired during an airport approach and landing is provided and analyzed. The flight survey measurements provided insight about the RF environment surrounding the aircraft during landing. The data were used to identify signals and their relative amplitudes to establish a baseline for further research.

This study demonstrated that the LaRC Lancair aircraft was a good choice for development of the ARMS. The ILS and VOR approach and landing instrumentation and GPS antenna and receiver were easily incorporated as part of the system. In addition, the Lancair aircraft is relatively inexpensive to operate; it is a small aircraft, requiring less fuel and a crew of only one to three people.

It was determined that several revisions to the data acquisition system could expedite and simplify operation. An automatic test setup capability is needed using previously recorded instrument and test setup data. In addition, the software needs to display maximum levels acquired from a spectrum analyzer trace with and without calibrations applied. A track ball attached to the operator's leg could replace the laptop touch pad and allow the operator to remain facing forward. Other additions could include automated acquisition and recording of aircraft altitude and compass heading that could be used to quickly determine an emitter location.

7 References

[1] Howell, C.T., III; Shelton, K.J.; Fisher, B.D.; Gallaher, D.A.; Johnston, S.L.; Rush, H.F., Jr.; Smith, C.D.; Trombetta, "The NASA Langley Research Center's General Aviation Baseline Research System", Proceeding of 22nd Digital Avionics Systems Conference 2003, Volume 2, October 12 – 16, 2003.

[2] FAA CFR Title 14: Aeronautics and Space, Part 23 "Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes", FAR 23.561 General, October 2006.

[3] FAA Advisory Circular AC43.13-2A: "Acceptable Methods, Techniques, and Practices – Aircraft Alterations": Chapter 1- "Structural Data", Revision 1977.

[4] FAA CFR Title 14: Aeronautics and Space, Part 23 "Airworthiness Standards: Normal, Utility, Acrobatic, And Commuter Category Airplanes", FAR 23.785: Personnel and Cargo Accommodations, Seats, berths, litters, safety belts, and shoulder harnesses", October 2006.

[5] C. A. Balanis, "Antenna Theory, Analysis and Design", John Wiley & Sons, 1982.

[6] W. L. Stutzman and G. A. Thiele,"Antenna Theory and Design", John Wiley & Sons 1981.

[7] P.A. Rizzi, "Microwave Engineering, Passive Circuits", Prentice Hall, 1988.

[8] Bennett Z. Kobb, Wireless Spectrum Finder, McGraw-Hill, 2001, ISB 0-07-137506-6.

[9] NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management (Redbook), http://www.ntia.doc.gov/osmhome/redbook/redbook.html.

Appendix A: "Out-Of-Band" Calibration

Section 5.1 discusses full RF spectrum data collected for a sample approach & landing, using the ARMS configuration shown in Figure 5-14. All this data is affected by the characteristics of the aircraft Comant CI 159C dual-band V-Dipole antenna. For the intended NAV RF bands, the Comant CI 159C antenna gain characteristics are predictable and well understood. However, most antennas also perform fairly well at frequencies outside their intended RF bands. One possible goal in evaluating broad band data is to identify signals that are present in a particular geographic location. The full RF spectrum plots of Section 5.1 are fully suitable for identifying available signals. However, if quantitative estimates of signal strength are required, it becomes necessary to obtain information about the ARMS antenna's directivity, reflection loss and resistive loss over the entire range of radio frequencies. Directivity plots for a typical dipole antenna (of varying length) are shown in Figure A-1. These plots apply to standard dipole antennas, rather than the Comant CI 159 V-Dipole antenna, but are useful to provide insight into how the aircraft antenna pattern can be expected to change as the antenna is used above its intended frequency band.

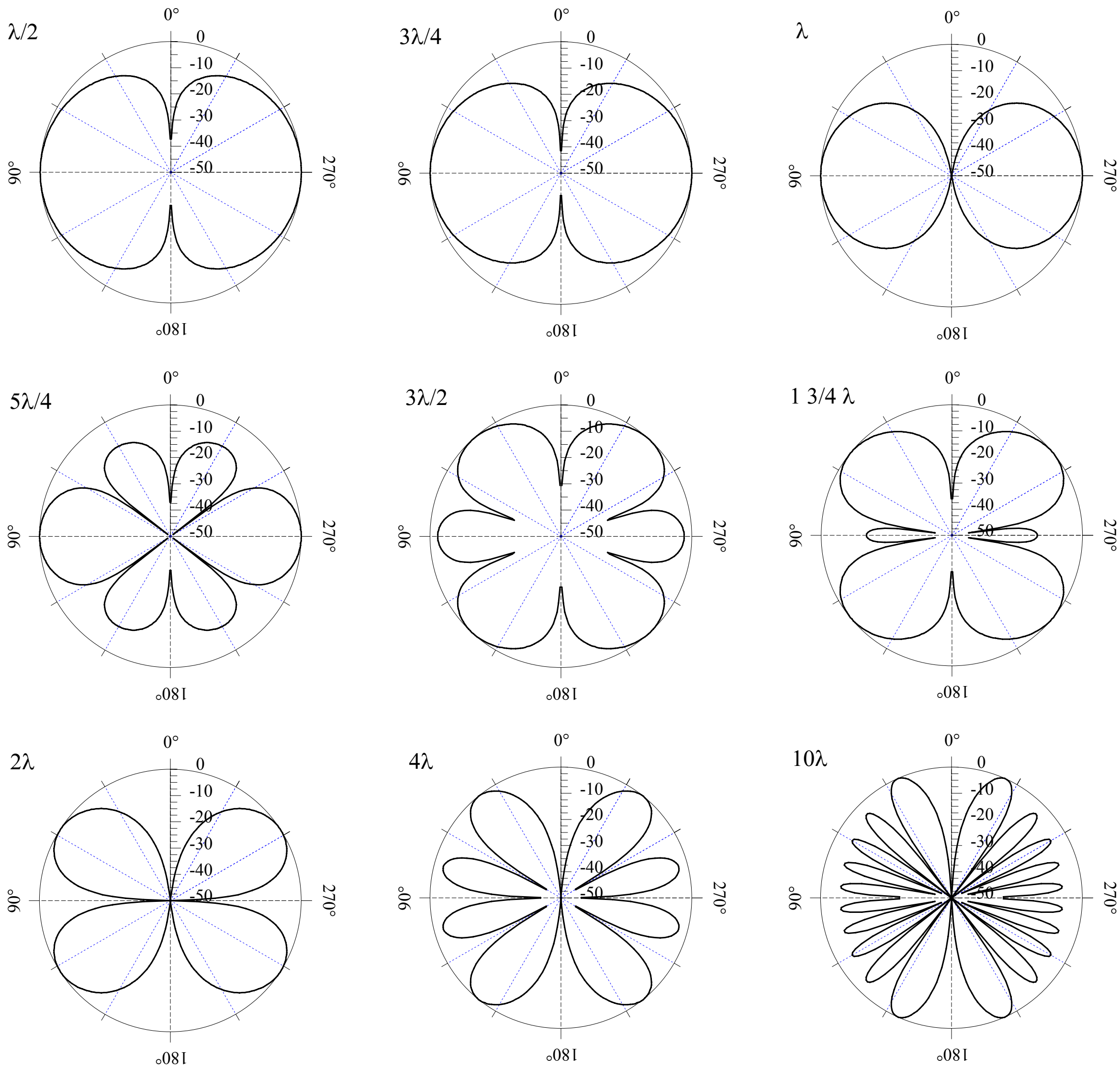


Figure A-1: RF Directivity plots D_θ/D_{max} , on dB scale, of a dipole antenna of increasing electrical length (cross sectional cuts).

The directivity plots of Figure A-1 were generated using a standard dipole gain formula in equation A-1 [ref. 5].

$$D_\theta = 20 \log \left| \frac{\cos\left[\frac{\beta l}{2}\cos(\theta)\right] - \cos\left(\frac{\beta l}{2}\right)}{\sin(\theta)} \right| \text{ (dB)}, \qquad \text{[Eq. A-1]}$$

Where:

l= antenna electrical length (in multiples of λ),

$\beta = 2\pi/\lambda$,

λ=the wavelength of the signal.

Assuming that the CI 159C antenna is designed for $\lambda/2$ at 113 MHz, it would have an electrical length of 4.42λ at 1000 MHz, and would have a maximum pattern complexity comparable to the 4λ plot shown in Figure A-1. From Figure A-1, it can readily be seen that tens-of-dB signal power may be lost by orienting the aircraft antenna such that

the transmitter is located in a pattern null. The dipole comparison is useful for understanding that a 90 degree sweep in aircraft heading during data acquisition will likely provide a maximum antenna directivity at any frequency.

It should also be noted that the maximum directivity (D_{max}) increases as the electrical length (l) increases. An approximation of this relationship for the V-Dipole antenna is shown in Figure A-2 [ref. 6]. Maximum directivity is given in dBi.

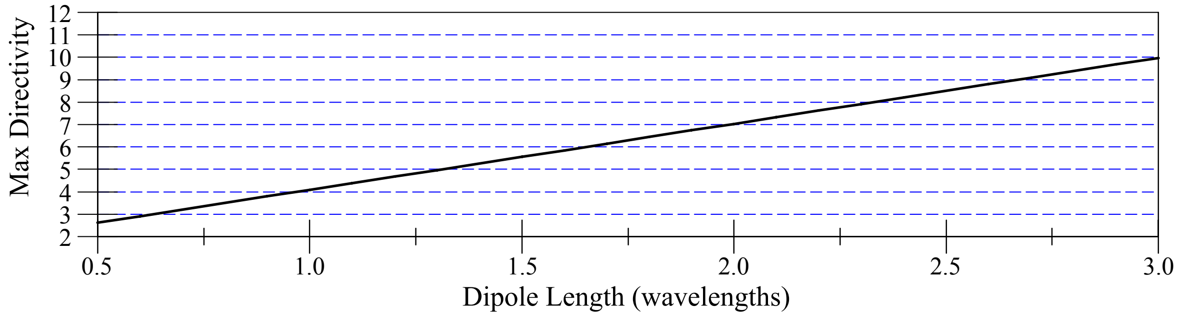


Figure A-2: V-Dipole D_{max} approximation.

Antenna reflection loss (L_{Refl}) may be obtained from a typical VSWR measurement on the aircraft antenna and applying Equation A-2 [ref. 7]:

$$L_{Refl} = 10\log\left[\frac{(VSWR+1)^2}{4 \cdot VSWR}\right] \text{ (dB).} \qquad \text{[Eq. A-2]}$$

Figure A-3 shows a plot of L_{Refl},, measured over the 30 to 1000 MHz RF band, on the Comant CI 159C antenna.

In general, most practical antennas are not constructed with lossy, or resistive components, and the antenna resistive loss (L_{Res}) can be ignored.

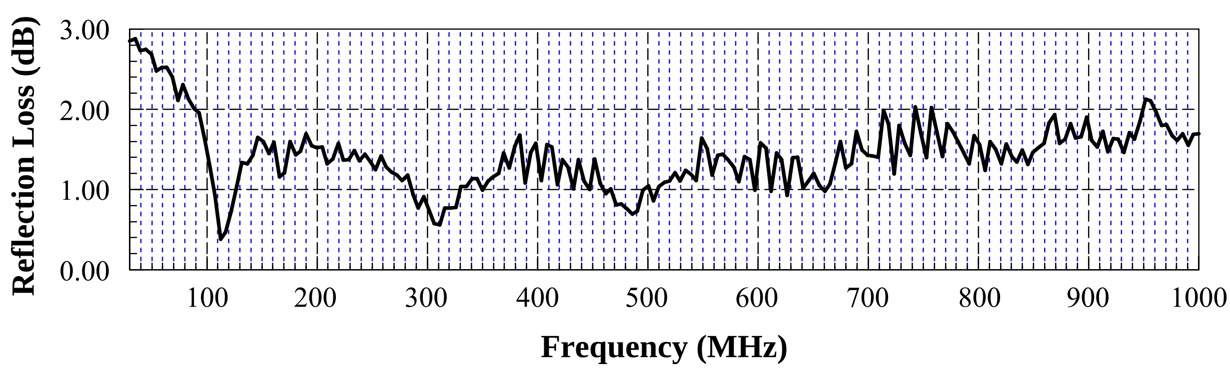


Figure A-3: Reflection Loss L_{Refl} for the Comant CI 159C dual-band V-Dipole antenna.

Also, it is important to evaluate cable losses, connectors and other in-line passive components, when using an on board aircraft antenna outside its intended RF band. For example, the Mini-Circuits zfsc-2-1b power divider

(splitter) is specified to have a 3dB insertion loss from 5 to 500 MHz. Therefore, additional insertion loss measurements above 500 MHz should be performed as part of a rigorous calibration process.

If necessary, all components of the aircraft antenna gain ($G_{AC\_Ant} = D_{AC\_Ant} - L_{Refl} - L_{Res}$) can be measured directly, together on the aircraft. It would be easiest for such a measurement to include the aircraft cable loss and power divider loss also. A diagram of such a proposed measurement setup for measuring antenna gain is shown in Figure A-4.

It is important that all measurements occur in the same cross-sectional plane, so the Reference Antenna should be placed on a movable platform equal in height to the aircraft antenna for all measurements. The Comant CI 159C antenna has a maximum linear dimension (D) of 35.34 inches (89.76 cm). Using the far-field boundary approximation of $2D^2/\lambda$, the maximum far field boundary of this antenna, over the frequency range of 30 to 1000 MHz, is 5.37 meters. Therefore the measurement distance radius, r, should be greater than 5.37 meters. Eight cross-sectional cuts are shown in Figure A-4, resulting in 16 measurement locations. The actual number of measurement locations may be increased depending upon the highest measurement frequency. The aircraft antenna gain may then be determined for each angle (θ):

$$G_{AC\_Ant\_Cbl\_Pdiv} = P_{Rcv} + L_{Prop} + L_{Test\_Cbl} - P_{Xmt} - G_{Xmt}\ (dB), \qquad \text{[Eq. A-3]}$$

Where:

$G_{AC\_Ant\_Cbl\_Pdiv}(\theta,f)$ = Aircraft Antenna Gain, including aircraft cabling and zfsc-2-1b RF power divider,

$P_{Rcv}(t,f,n,lat_{rcv},lon_{rcv},alt_{rcv})$ = Power received at the aircraft radio connector for each frequency (f), each environmental transmitter (n), and aircraft position (lat, lon, alt), at a given time (t), (as defined in Section 5.2),

$L_{Prop}(f,n, lat_{rcv}, lon_{rcv}, alt_{rcv}, lat_{source}, lon_{source}, alt_{source})$ = |Propagation loss| between each signal source (n) and aircraft antenna, for each frequency (f), (as defined in Section 5.2),

$L_{Test\_Cbl}(f)$ = Test cable loss (all test cables combined),

$P_{Xmt}(f)$ = Power transmitted from the spectrum analyzer tracking source,

$G_{Xmt}(f)$ = Reference Antenna Gain.

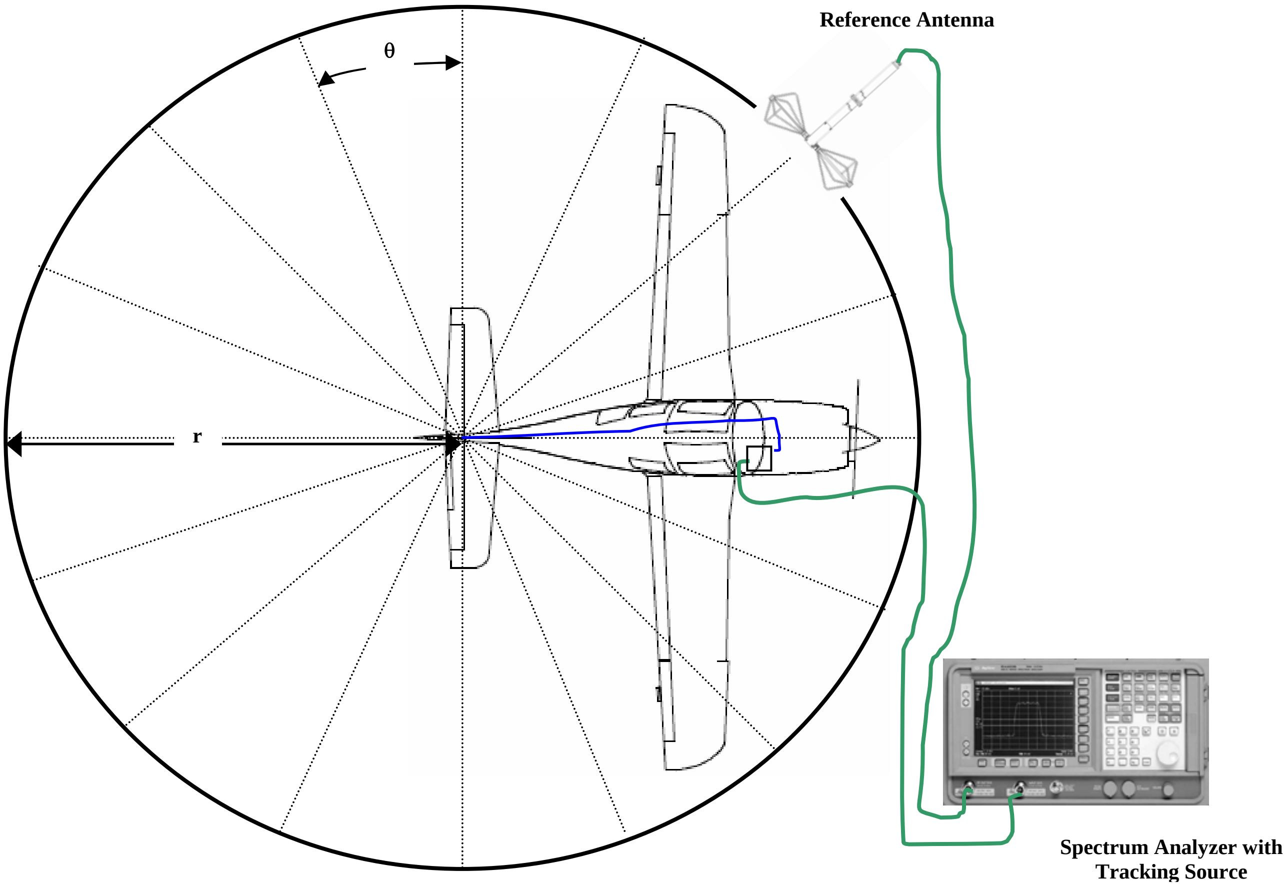


Figure A-4: Proposed setup for measuring ARMS antenna gain over a broad range of frequencies.

As described previously in Equation 5-2, the propagation loss may be determined from: L_{Prop}= 20Log[c/(4πfr)]. Equation A-3 assumes that the Reference Antenna is transmitting.

It is important to note that ground reflections may significantly affect measurement data, especially if the flooring is moist or has metal content, such as rebar. It is suggested that RF absorptive material be placed on the ground between the aircraft antenna and reference antenna.

This proposed measurement setup for $G_{AC\_Ant\_Cbl\_Pdiv}$ is intended to be a good estimate for calibration of in-flight data, when the direction of the transmitting source is known. It is important to note that the aircraft itself will alter the gain pattern when intersecting other cross-sectional planes.

Appendix B: Airworthiness of Mechanical Installation

Static inertia loads and ultimate load factors for emergency landing conditions are addressed in "FAR 23.561 Airworthiness Standards: Normal, Utility, Acrobatic, And Commuter Category Airplanes" general regulations [ref. 2]. It states that occupants must have a reasonable chance of escaping injury when experiencing static inertia loads corresponding to the load factors listed in Table B-1. Also, items of mass that could injure an occupant are weight limited by static inertia loads corresponding to the ultimate load factors as listed in Table B-1. "Advisory Circular AC43.13-2A Acceptable Methods, Techniques, and Practices - Aircraft Alterations, Chapter 1 Structural Data" further specifies that supporting structure and attachments must be able to withstand additional load factors (Table B-1) as contributed by installed equipment weight [ref. 3]. It defines ultimate load factors as the load factor multiplied by a prescribed safety factor to give the maximum forces that can be safely experienced. The load factors were used to determine the stresses and resulting positive margins-of-safety on the hardware installed, including brackets, plates, and fasteners.

Table B-1: Static Inertia Load Conditions and Ultimate Static Load Factors

Direction of Force	Static Inertia Load Conditions	Ultimate Static Load Factors
Forward	9.0 g	18.0 g
Upward	3.0 g	3.0 g
Sideward	1.5 g	4.5 g
Downward	6.0 g	None

The "FAR 23.785 Personnel and Cargo Accommodations, Seats, berths, litters, safety belts, and shoulder harnesses" regulation states that restraint systems and the supporting structure must be designed to support occupants weighing at least 215 pounds when subjected to the maximum load factors [ref. 4]. In addition, these loads must be multiplied by a fitting factor of 1.33 when determining the strength of all fittings.

To determine the allowable maximum weight (hardware and equipment combined) for the side pallet a structural analysis was performed. First, a maximum seat weight was determined using the following formula with a seat weight of sixteen pounds and occupant weight of 215 pounds:

$W_t = (W_o + W_s) * ff$, (Eq. B-1)

Where:

W_t = Total seat weight,

W_o = Occupant weight,

W_s = Actual seat weight,

ff   = Fitting Factor.

Then substituting:

$W_t =$ (215 lbs. + 16 lbs) * 1.33,

W_t = 307.23.

Assuming the sideward loading condition was dominant in this instance, an ultimate static load factor of 4.5 and a total seat weight of 307.23 pounds from the previous calculation was used. The maximum allowable pallet weight was calculated using a ratio between the structural ultimate static inertia loads and the items of mass inertia loads as follows.

$4.5 * W_p = 1.5 * W_t$, (Eq. B-2)

$W_p =$ 1.5/4.5 * 307.23,

W_p = 102.4 lbs.

Where:

W_p = Maximum allowable pallet weight (hardware and equipment).

The analysis demonstrates that a maximum weight for the side pallet could not exceed 102.4 lbs. including hardware and equipment combined. This gives a sizeable margin-of-safety.

The forward portion of the side pallet utilized an angled bracket and was double mounted in the foot well region of the aircraft (Figure B-1). All brackets were fabricated from 2024-T42 aluminum, an aircraft quality material with the following properties; ultimate strength of 62,000 pounds per square inch (ksi), yield strength of 38 ksi, and shear strength of 37 ksi. All brackets were analyzed for crippling/buckling, tensile, and bearing stresses. All margins-of-safety were 1.3 or higher.

A bracket, enclosing the spectrum analyzer on all four sides, utilized the existing handle attachment point for mounting purposes (Figure B-2). A base bracket was attached to orient the analyzer in the desired angle. In the forward position, the pilot's seat belt brackets were utilized for restraining the instrument and rear brackets provided additional restraints. Again, 2024-T42 aluminum was utilized in the fabrication of these brackets. The brackets were analyzed for the same stresses as the side pallet and also had positive margins-of-safety.

Aircraft fasteners were utilized for installation of all hardware in the aircraft. The fasteners have a minimum tensile strength of 1690 pounds (load) and 84.5 ksi (stress) and minimum shear strength of 2125 pounds (load) and 74.9 ksi (stress) at full diameter, where the relationship between load and stress is defined as: Stress (ksi) = Load (lbs.) / Cross sectional area of fastener (sq.in.). As with the brackets, all mechanical design margins-of-safety were positive.

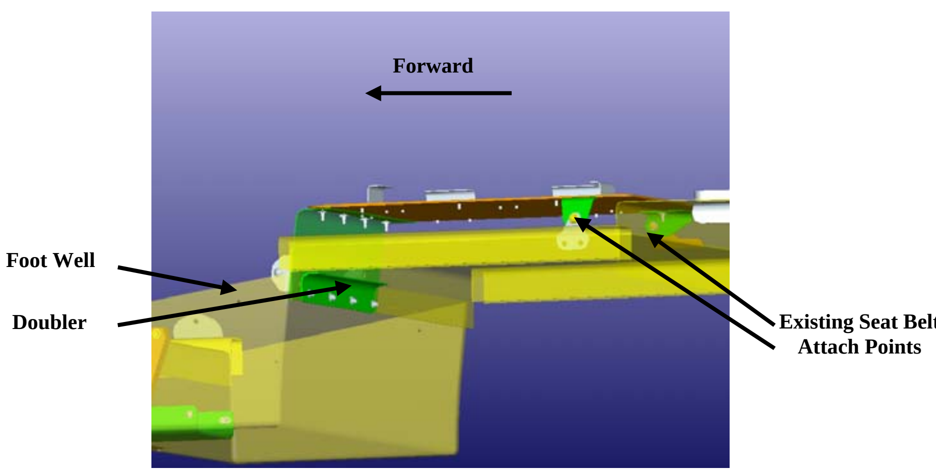


Figure B-1: Seat pallet and restraints for laptop design layout. Pallet maximum weight limit is 77 pounds. Analysis indicated margins-of-safety are positive for shear of 5.3 and tensile of 1.3.

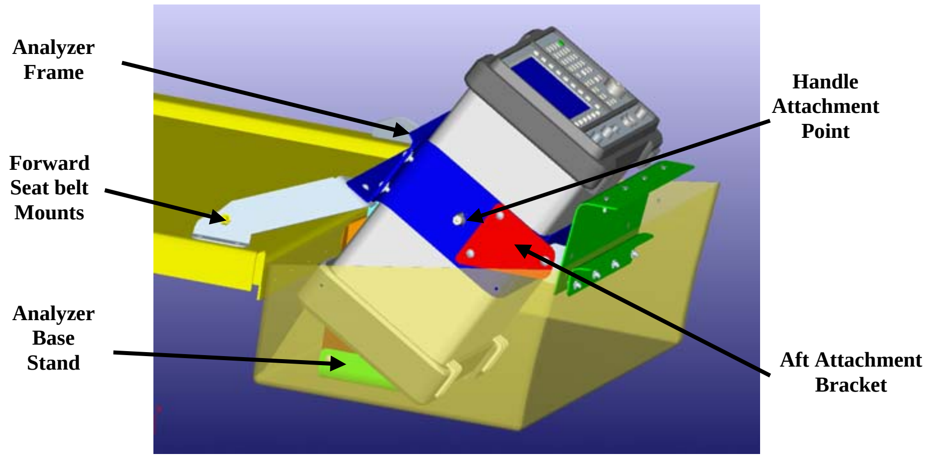


Figure B-2: Spectrum analyzer mount design layout. Analysis indicated high margins-of-safety for a shear of 7.0 and tensile of 2.9.

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14. ABSTRACT
Environmental radio frequency (RF) data over a broad band of frequencies (30 MHz to 1000 MHz) were obtained to evaluate the electromagnetic environment in airspace around several airports. An RF signal measurement system was designed utilizing a spectrum analyzer connected to the NASA Lancair Columbia 300 aircraft's VHF/UHF navigation antenna. This paper presents an overview of the RF measurement system and provides analysis of sample RF signal measurement data. This aircraft installation package and measurement system can be quickly returned to service if needed by future projects requiring measurement of an RF signal environment or exploration of suspected interference situations.

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